Sagittarius A* and its Environment

Mark Morris, UCLA

Outline

I. The central molecular zone: clouds & diffuse gas content
   - cosmic rays
   - interstellar mass budget: inflow, star formation, Galactic wind

II. The Galactic center magnetic field

III. Star Formation in the Galactic Center: massive stars & supernova
   - massive, compact, young clusters
   - Sgr A East

IV. The Galactic black hole and its environment

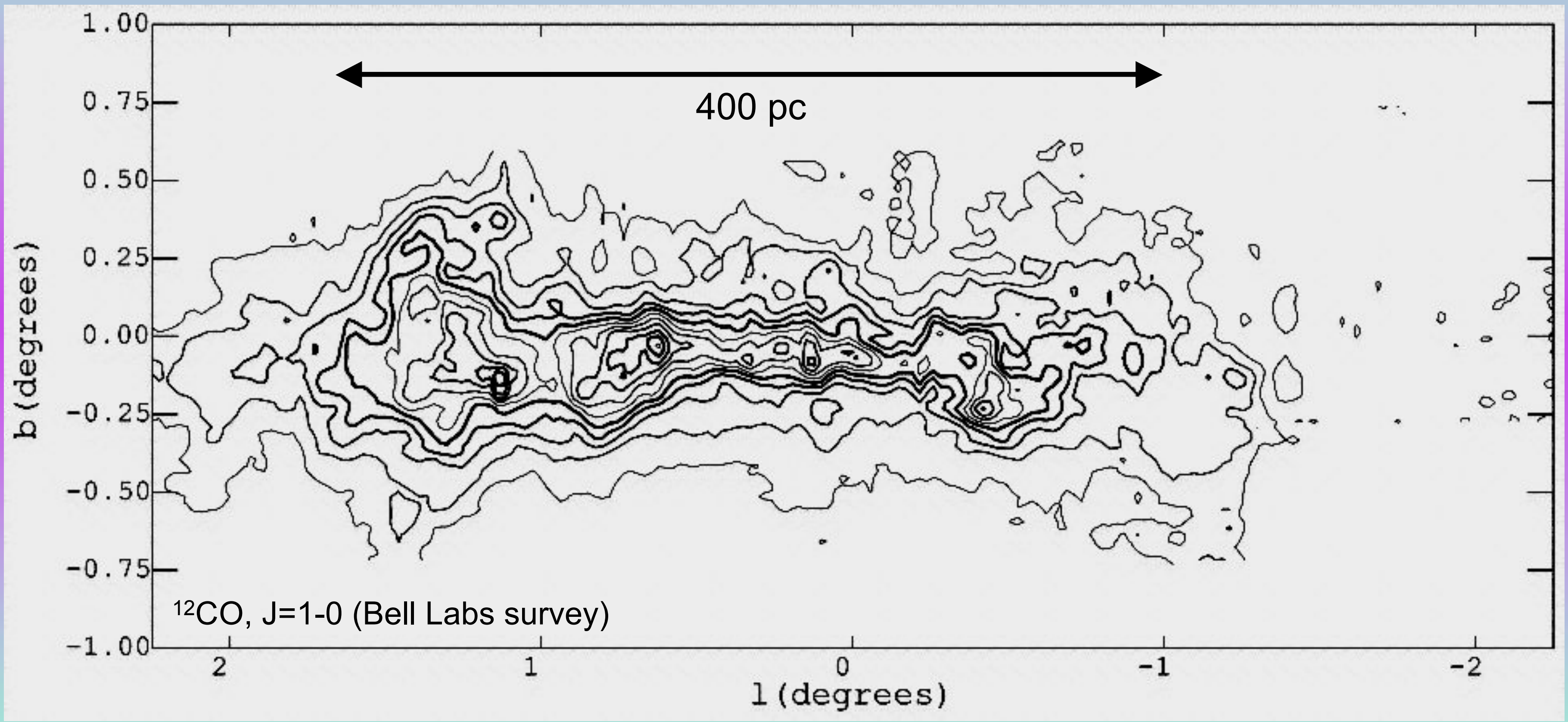
The Galactic center attracts our attention because it harbors phenomena not seen elsewhere, as well as far more extreme examples of phenomena occurring elsewhere.

2MASS/MSX

It links us to AGNs and to other distant beacons by giving us insight into the physical elements operating in such energetic environments.

Central Molecular Zone: the Galactic Center Arena

Total mass ~ 3-4 x 10^7 $M_\odot$ —> Σ ~ 440 $M_\odot$ pc^{-2}

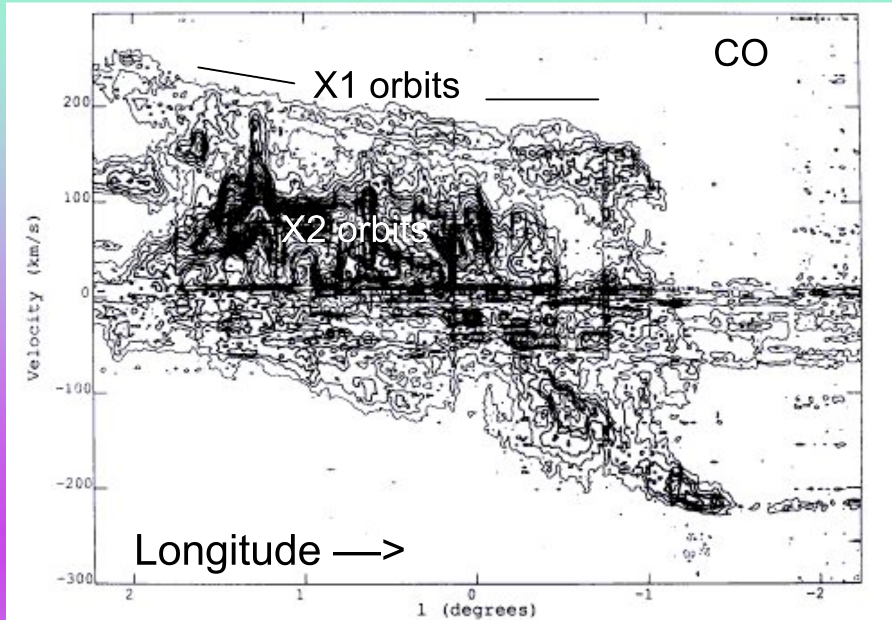


Scale of CMZ ~ scale of inner Lindblad resonance

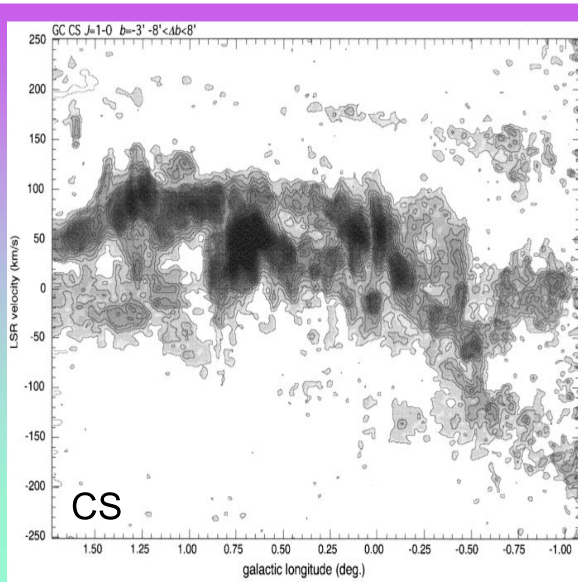
~ scale of Galactic center magnetosphere

~ scale of hot, X-ray emitting diffuse gas

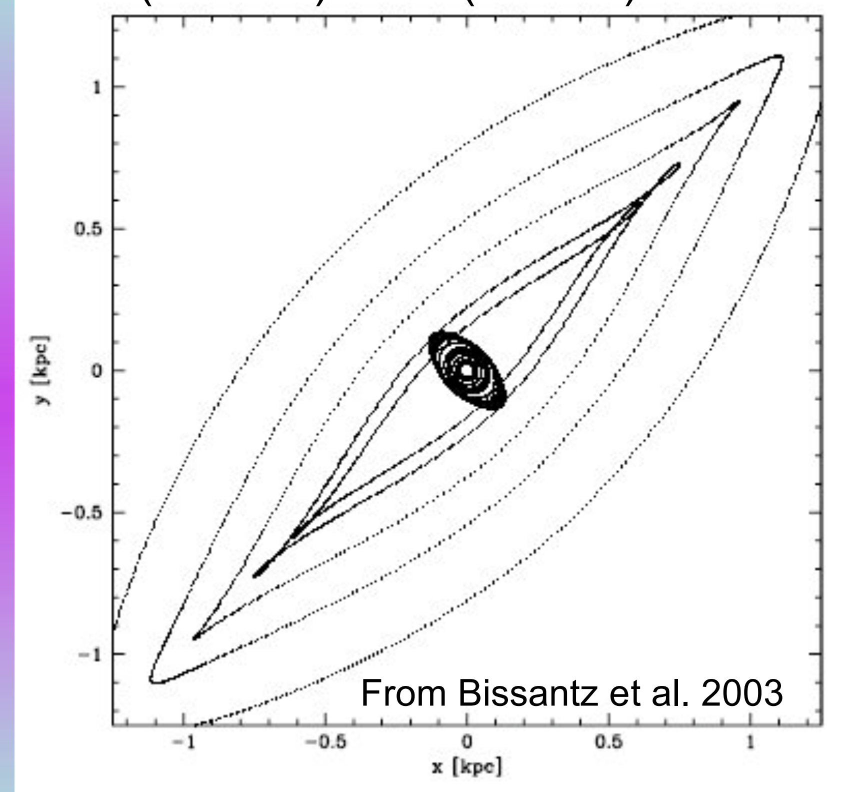
Gas in the CMZ responds to the bar potential, even though it is well within the 2.5 x 1 kpc bar.



Velocity —>



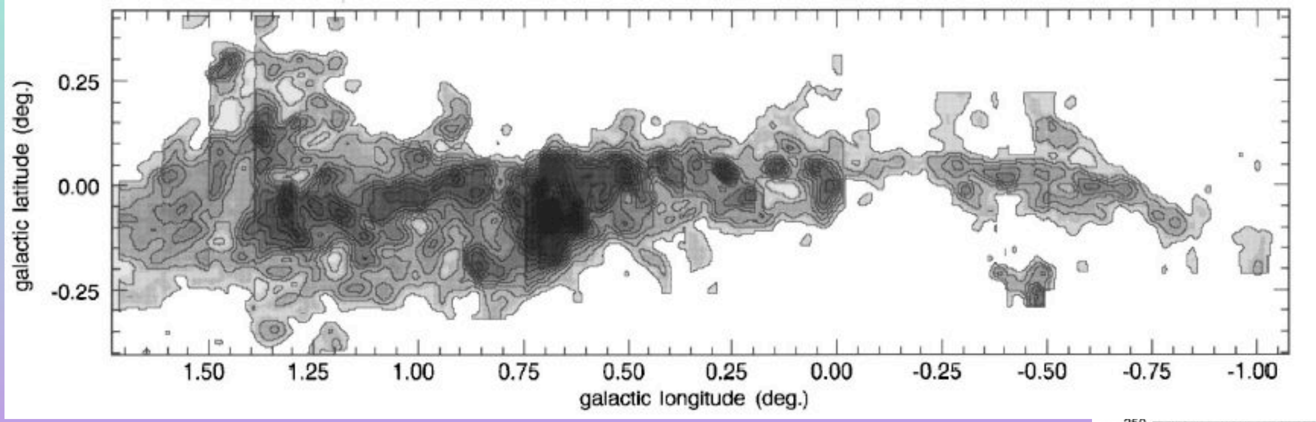
X1 (exterior) & X2 (interior) orbits



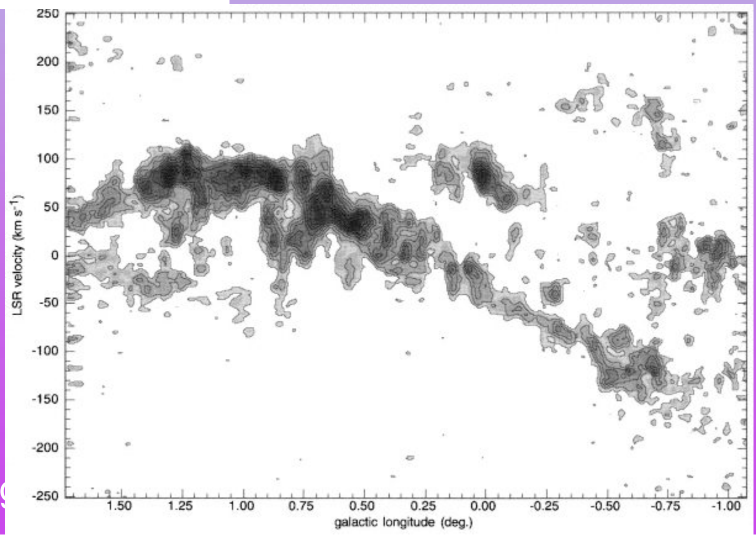
Binney et al. 1991: the gas becomes molecular at the innermost non-self-intersecting X1 orbit (the ILR), where it undergoes a compressive shock.

Molecular clouds in the CMZ are subject to strong tidal shear, so their morphology is often, if not usually, drawn out as a tidal stream, unless their density exceeds a critical value, ~ 10^4 cm^{-3} $(75\ pc/R)^{1.8}$.

The density of most clouds is not far from this, but many clouds on X2 orbits are seen to be streamers wrapping much of the way around the center.



e.g., the GC Bow (Tsuboi, Handa & Ukita 1999)



The residence time of molecular clouds in the CMZ is set by dynamical friction (Stark et al. 1991) and perhaps by magnetic drag (Morris 1994):

$\boxed{t_{res} \sim \text{several} \times 10^8 \text{ years.}}$

$\Rightarrow$ A mass inflow rate ~ 0.1 $M_\odot$ yr^{-1} is needed to maintain the CMZ.

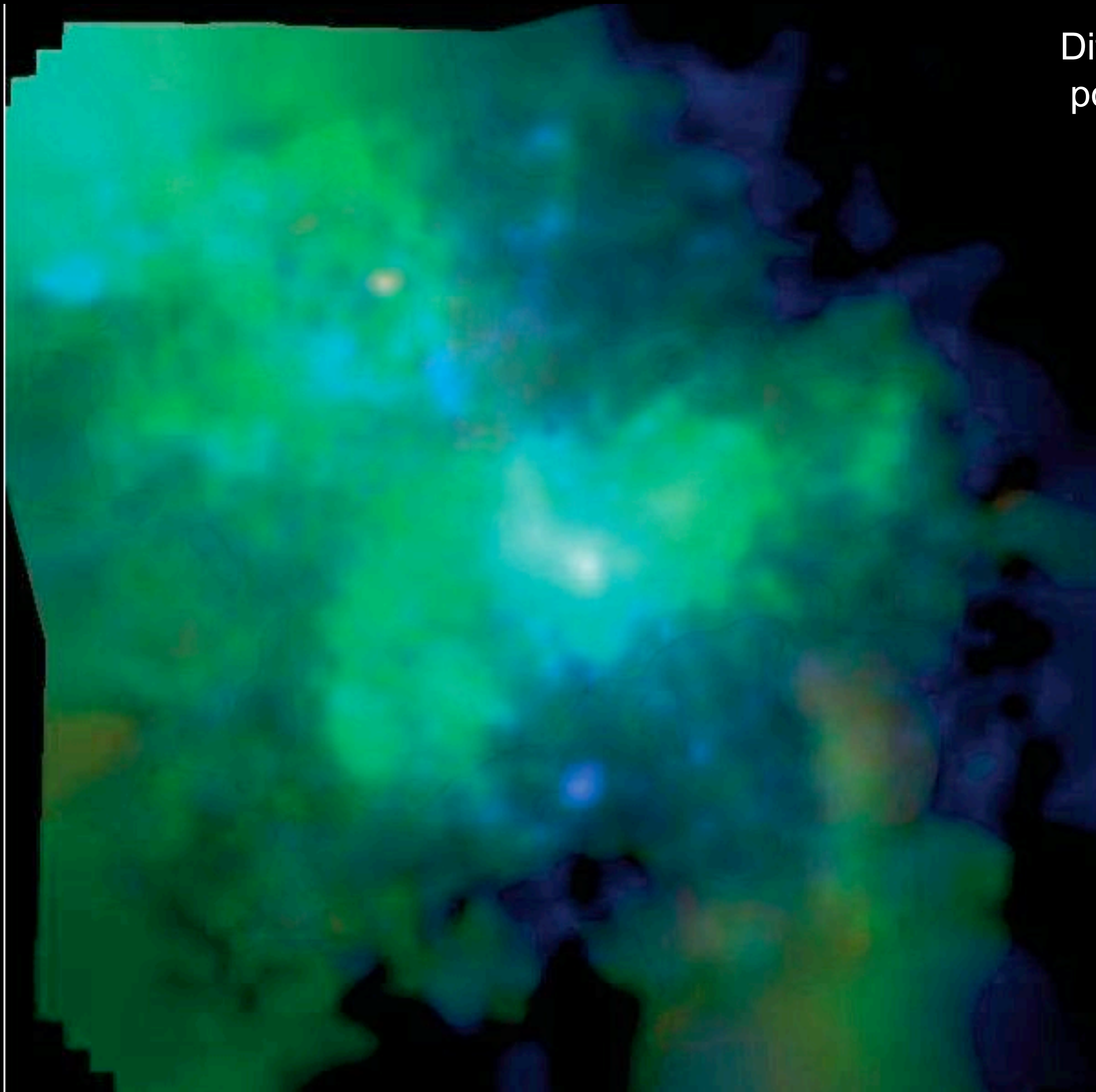
$\Rightarrow$ Over a Hubble time, this gives a total mass of 10^9 $M_\odot$, consistent with the mass of the central r^{-2} stellar cluster (the Nuclear Bulge).

$\Rightarrow$ The fate of most of the mass inflowing to the CMZ is to form stars, and the r^{-2} stellar cluster has resulted from sustained star formation over a Hubble time, perhaps punctuated with a few bursts
(Serabyn & Morris 1996; Figer et al. 2004).

Chandra Imaging of the Galactic Center

Fred Baganoff, PI
+ ACIS team
+ Mike Muno (UCLA)

3-color, 2 - 8 keV
adaptively smoothed



Diffuse X-ray Emission
point sources removed

Muno et al. 2004
17’ Chandra field
(40 pc)

red: 0.5-2 keV
green: 2 - 4 keV
blue: 4 - 8 keV

The Hot, Diffuse Gas (domain of X-rays)

Two-temperatures:

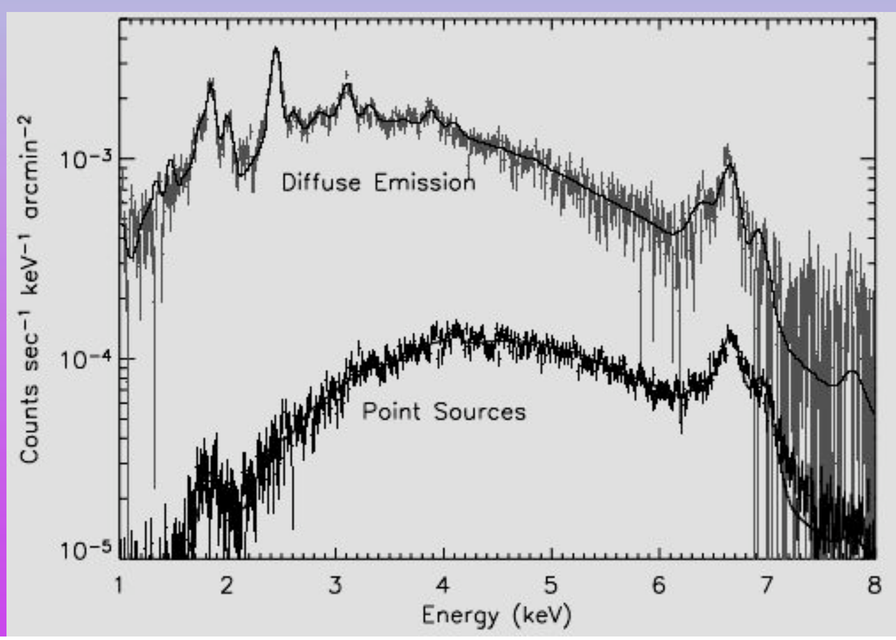
0.8 keV — <> attributable to supernovae

<> irregularly distributed –> young

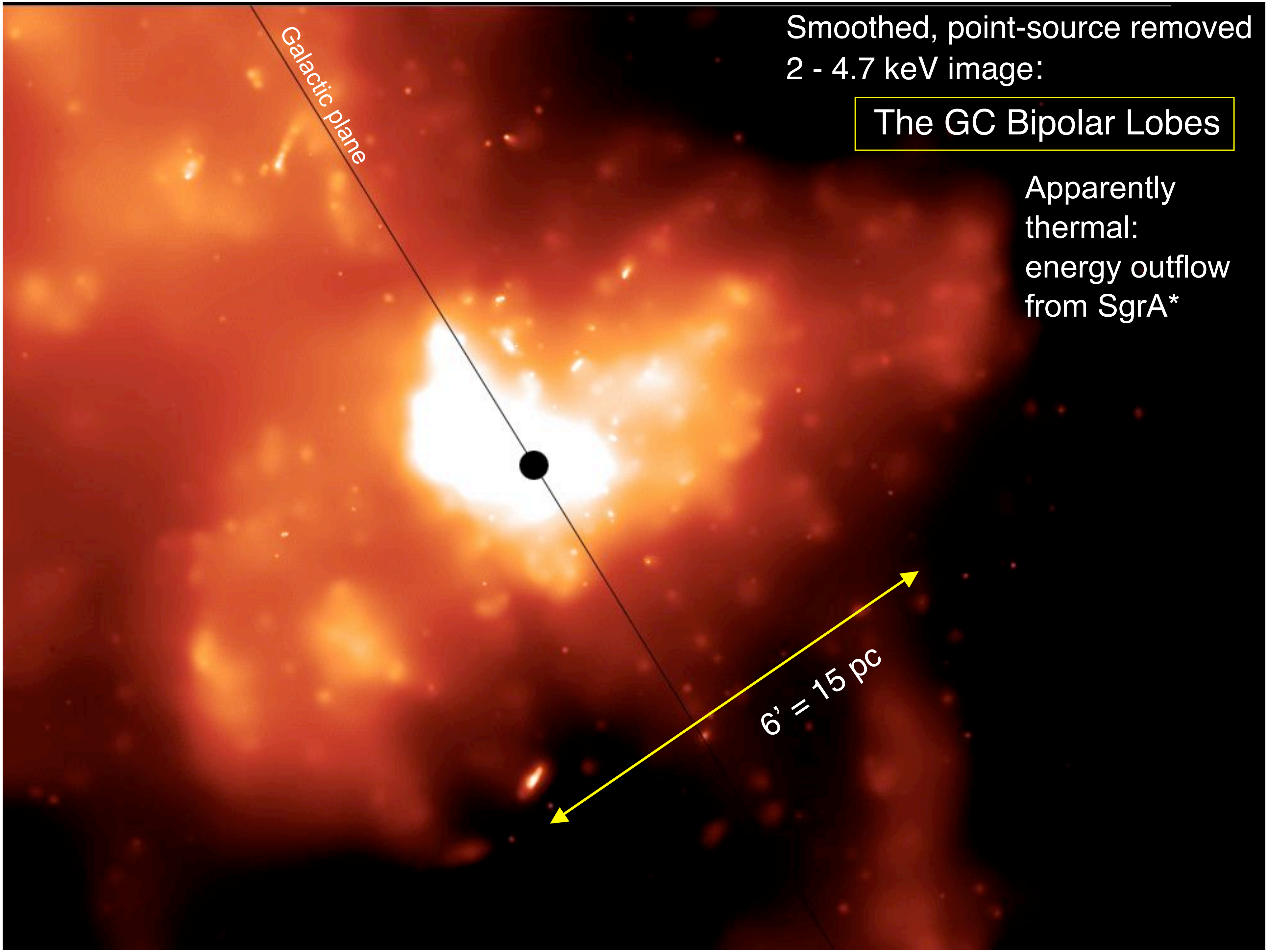
8.0 keV — <> uniform, 200 x 300 pc (like CMZ)

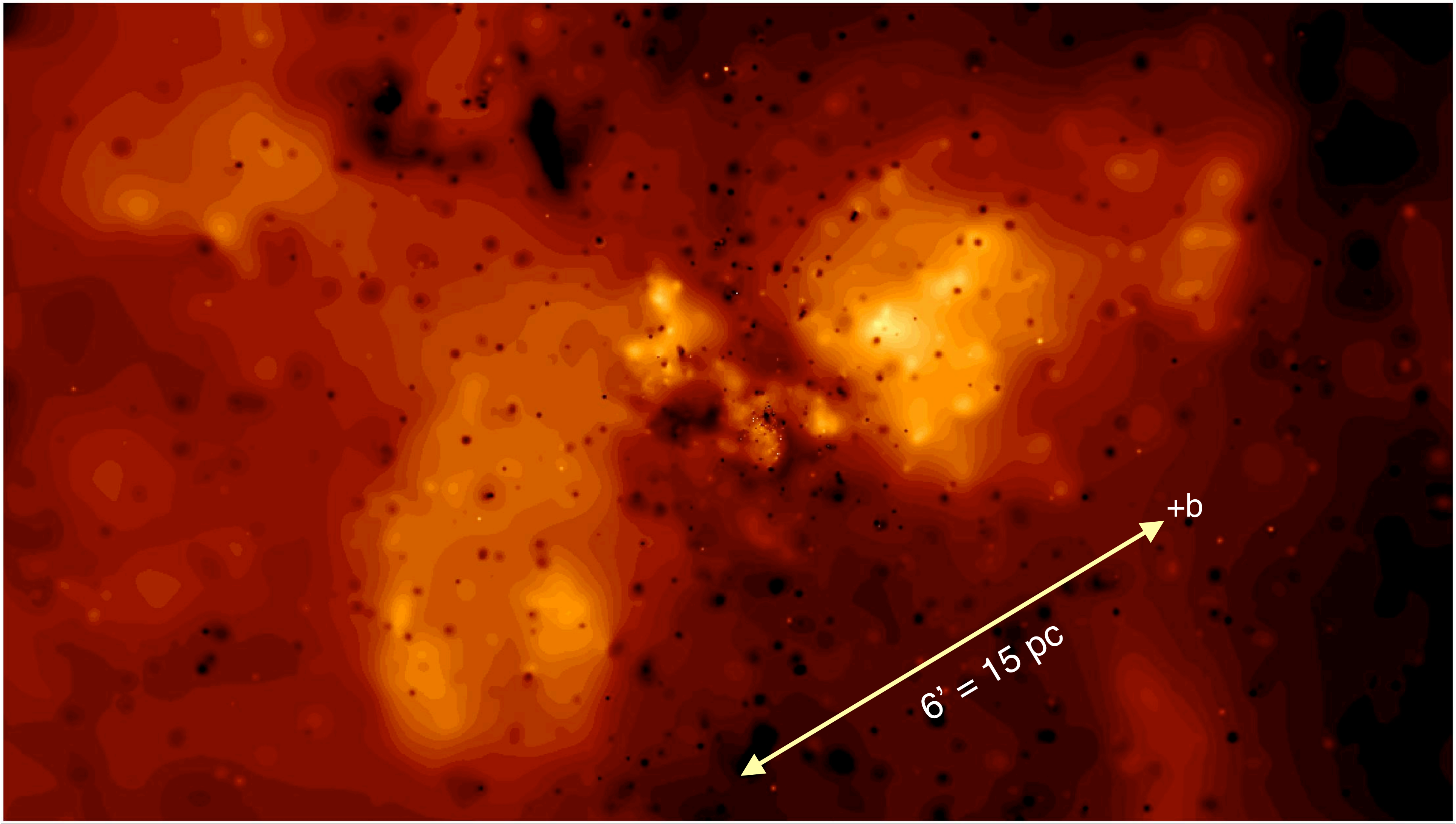
<> 10^{40} ergs s^{-1}

<> energy source yet to be clarified, but probably not undetected point sources

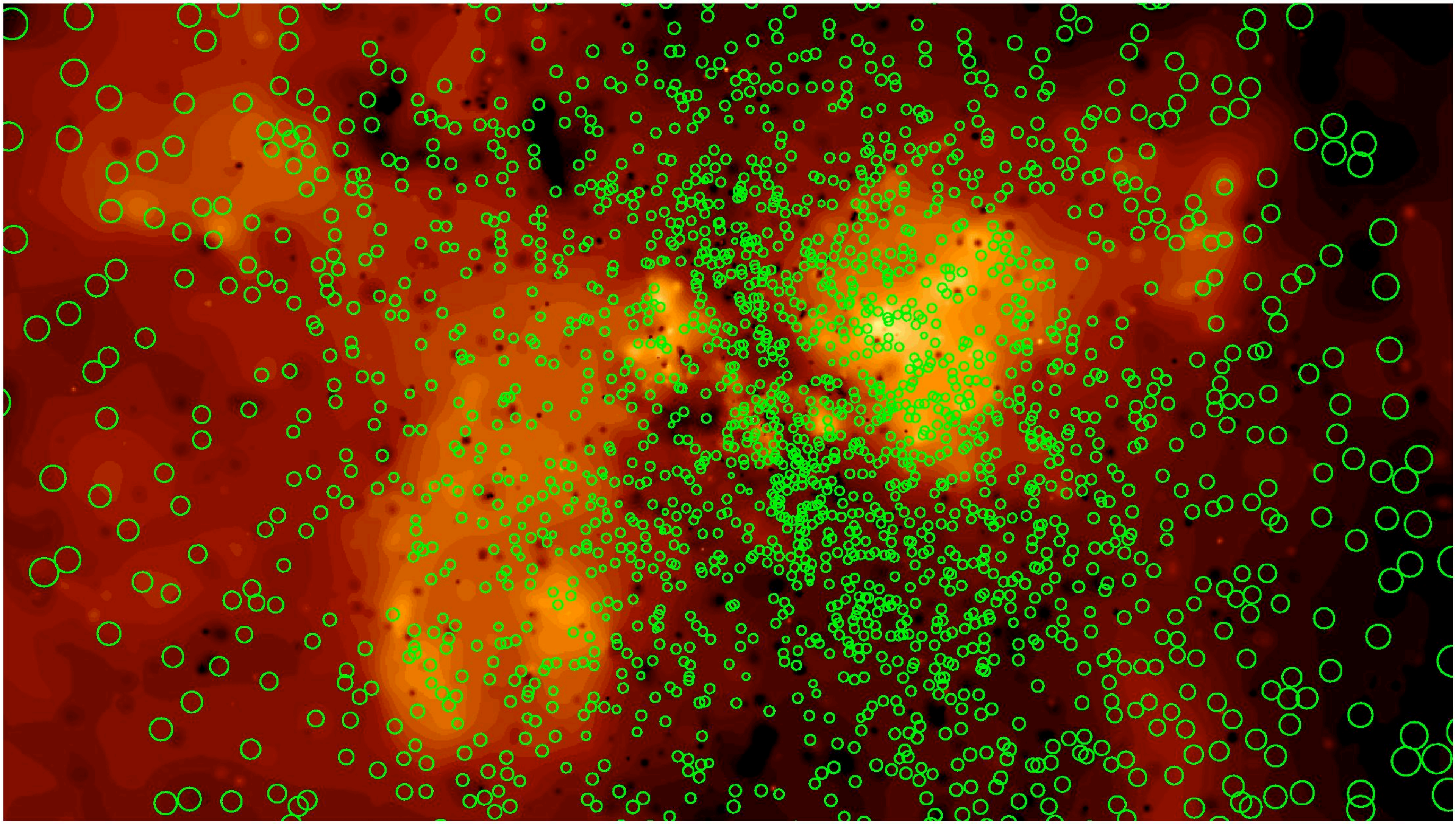


Unbound ==> Galactic wind,
leaving behind a helium plasma,
because only H can escape.
(Muno et al. 2004; Belmont, Tagger, et al. 2005 preprint)


Smoothed, point-source removed
2 - 4.7 keV image:
The GC Bipolar Lobes
Apparently
thermal:
energy outflow
from SgrA*
Galactic plane
6' = 15 pc



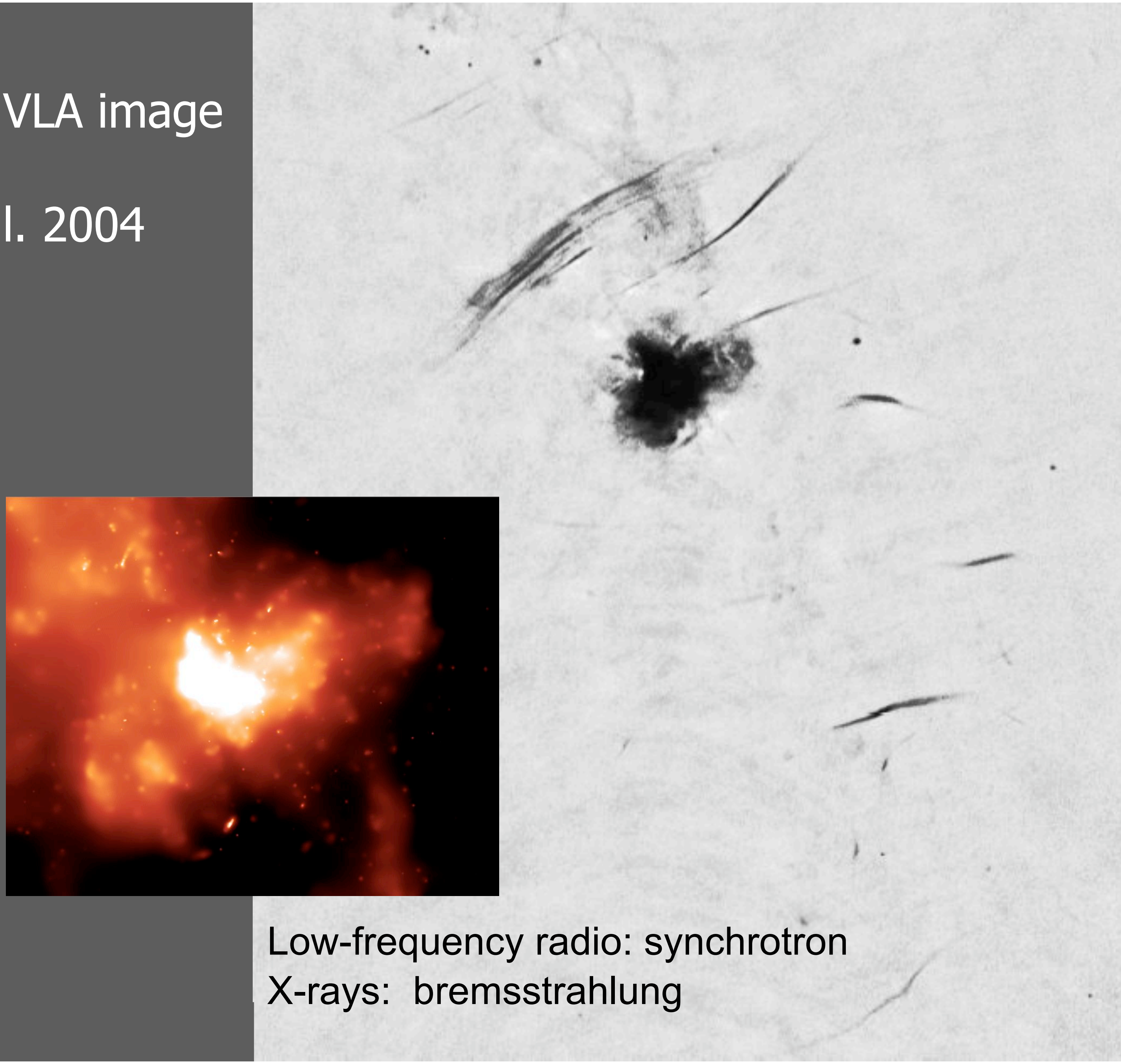
Ratio: soft (2– 4.7 keV) / hard (4.7 – 8 keV) emission
(most point sources removed)



Locations of point sources (Muno et al.)

330 MHz VLA image

Nord et al. 2004



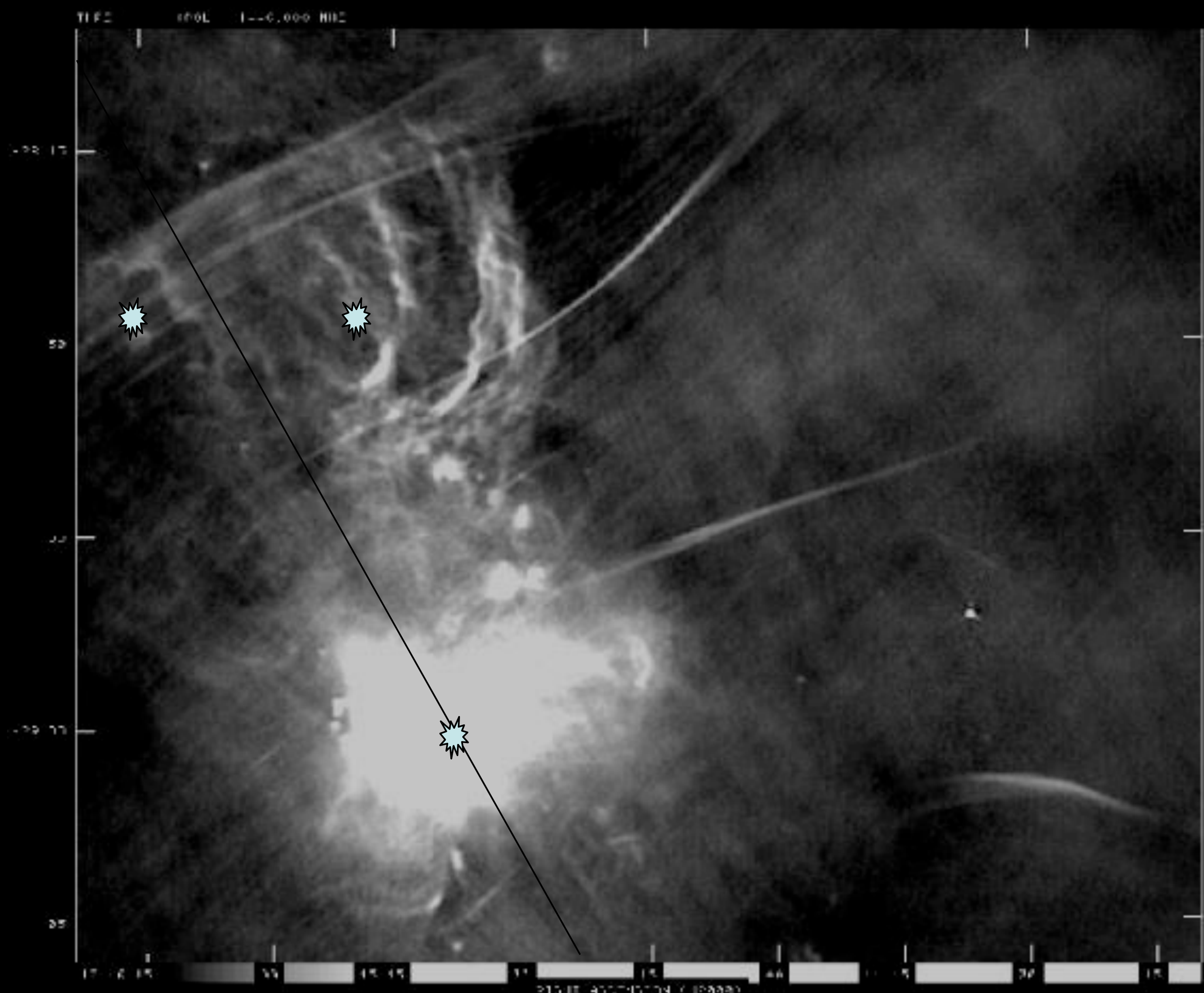
Low-frequency radio: synchrotron

X-rays: bremsstrahlung

The GC Bipolar Lobes

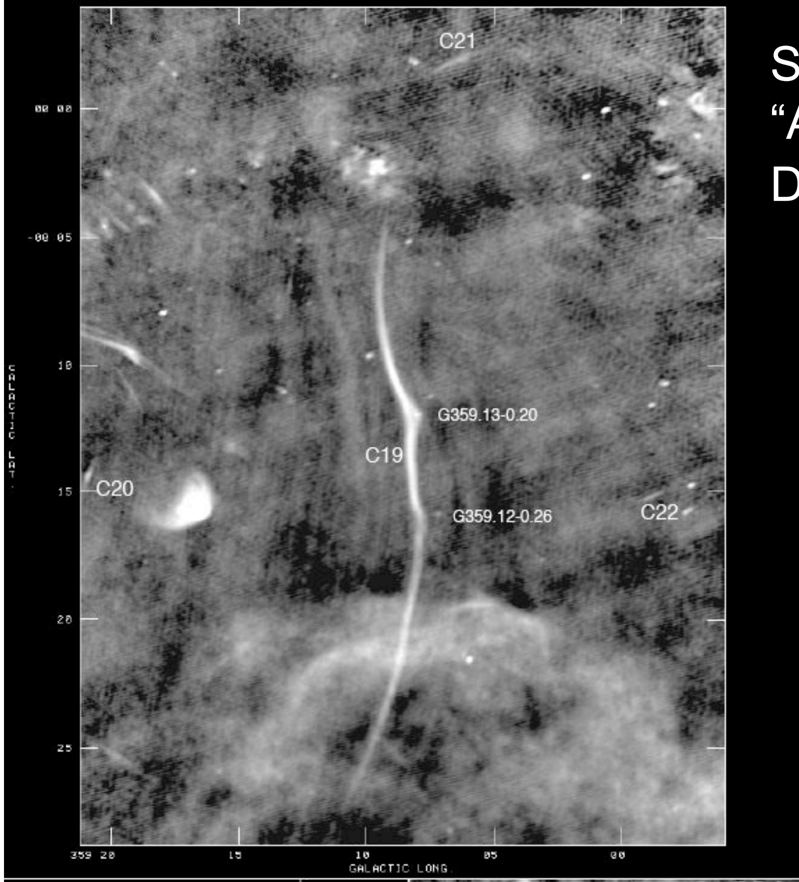
- Sgr A* is implicated by symmetry and means
- time scale for outer portions to flow from
  Sgr A*: 10^4 yr (v_{out}/1000 km s^{-1})
  comparable to Sgr A East expansion time
- separate lumps interpreted as separate episodes spaced by a few thousand years.
- $T_{gas} \sim 2 \times 10^7$ K
- $n_{gas} \sim 1$ cm^{-3}
- mass per blob ~ 1 $M_\odot$

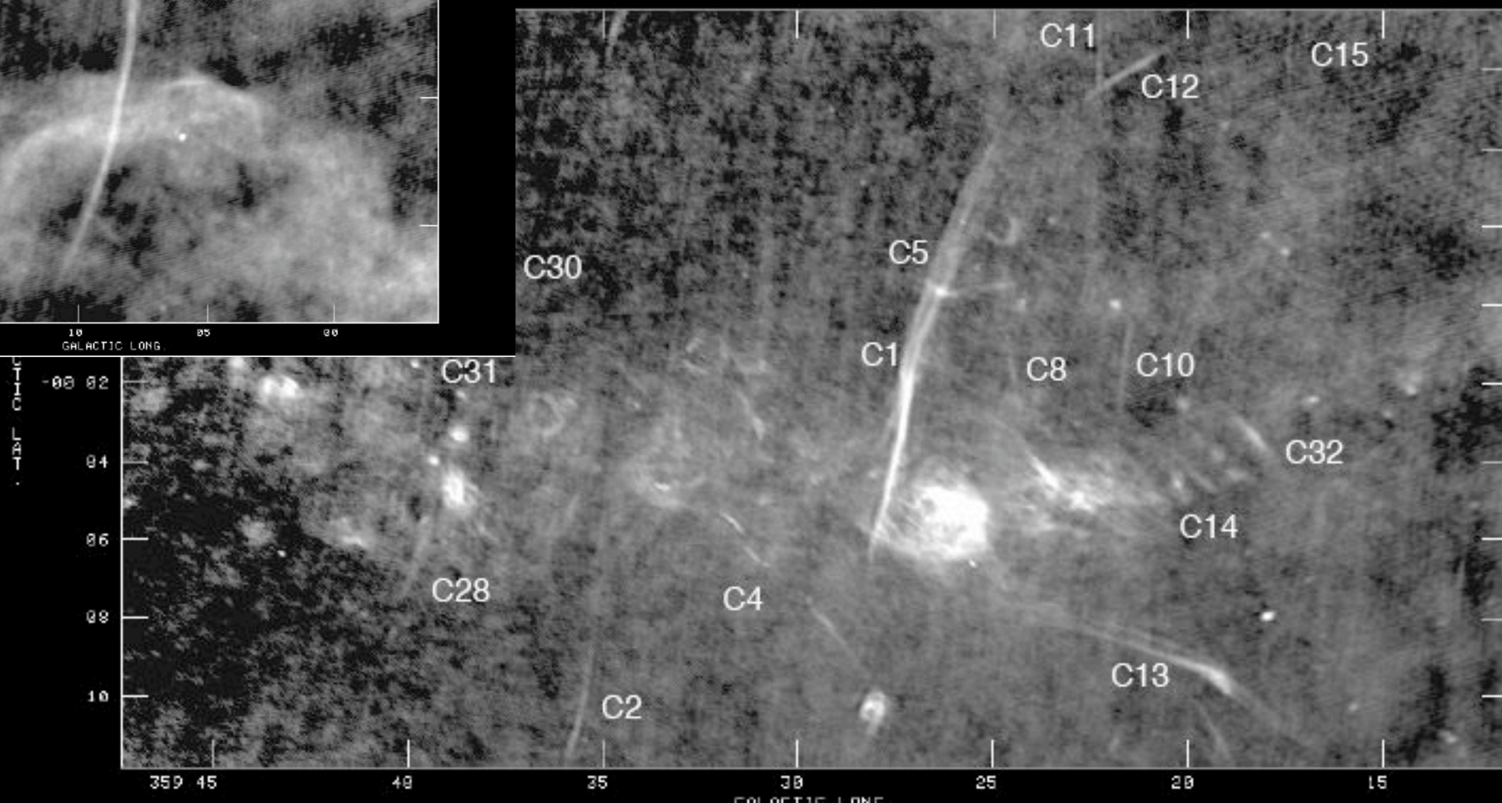
The Galactic Center Magnetosphere



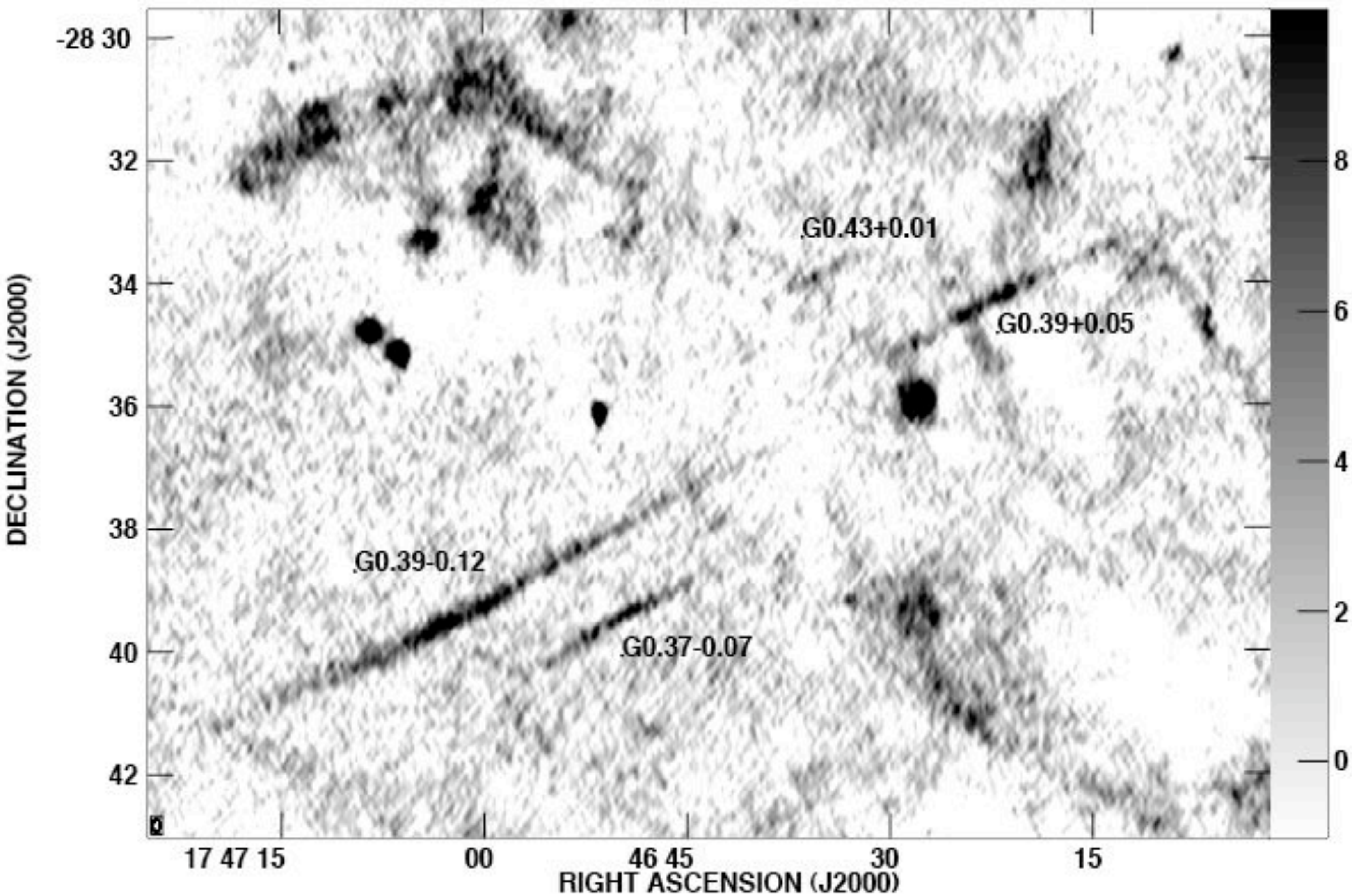
Lang, Morris, Echevarria 1999; 20-cm VLA

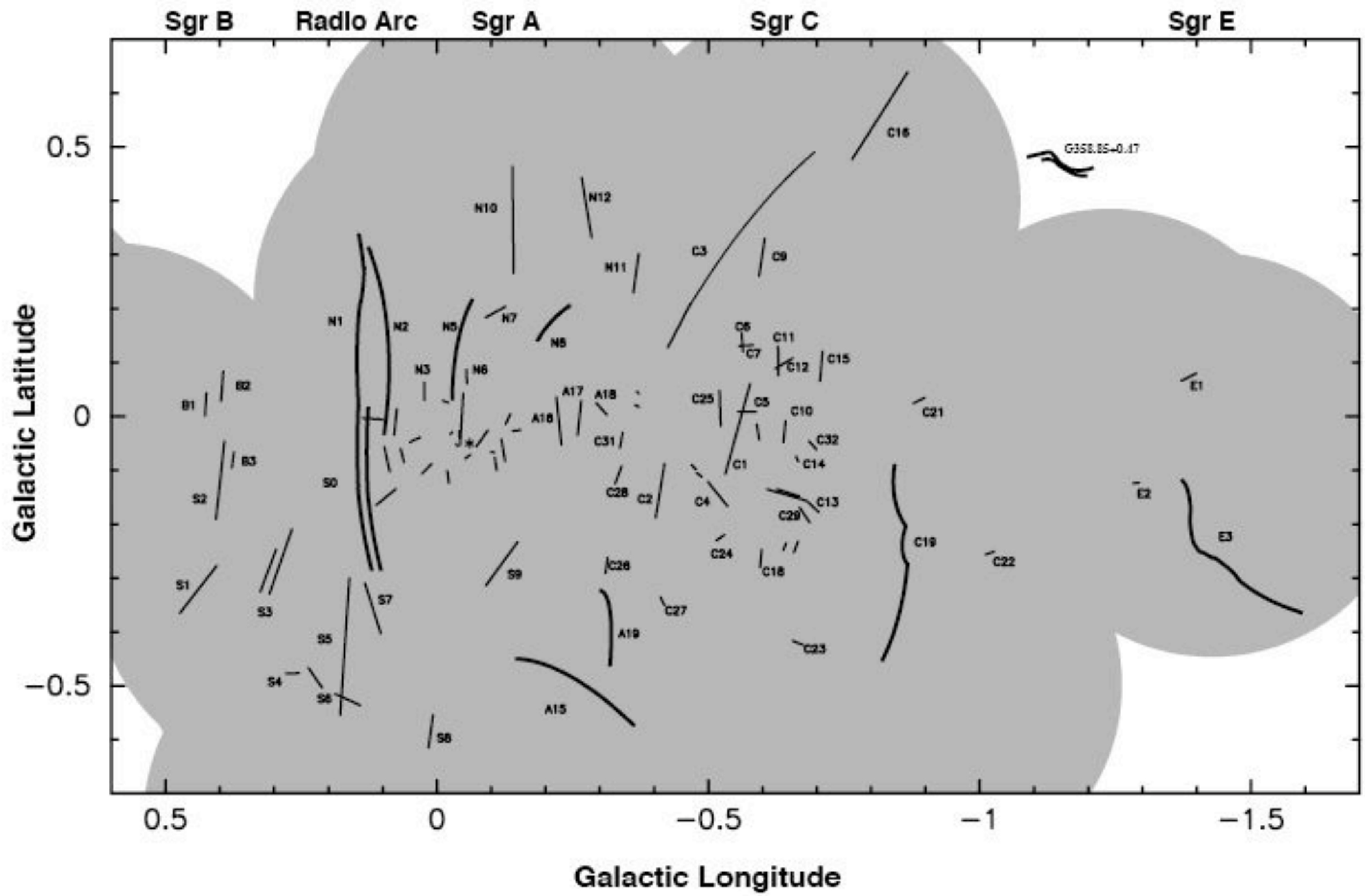
Samples from Yusef-Zadeh, Hewitt & Cotton 2004: “A λ20cm Survey of the Galactic Center Region I: Detection of Numerous Linear Filaments”





And from Nord et al. 2004, observing at 330 MHz:





Schematic of all non-thermal filaments (NTF's) from Yusef-Zadeh et al. 04

Original conclusion from the non-thermal filaments (NTFs):

The inner 100 pc or so has a pervasive milligauss, dipolar magnetic field.

[Based on: 1) rigidity of field lines in the face of ISM turbulence, and
2) lack of a confinement mechanism for the NTFs, if they are simply isolated structures. The 10^8 K gas is not sufficient.]

Also, this field could be accounted for with a natural Galactic evolution model (Chandran, Cowley & Morris 2000)

This idea is being questioned as a result of:

1) detection of some filaments which do not conform to the vertical trend

2) equipartition arguments

3) insufficient support from Faraday, Zeeman measures

Alternative suggestions range from 10 to 100 μgauss.
However, all of these objections can be countered.

The Double Helix Nebula
(Morris, Uchida, & Do, in prep.)

24 μm Spitzer/MIPS image above the Galactic center..

A torsional Alfvén wave?

If nonthermal, then need GeV electrons.

B

Figure will be published soon

25 pc

Cosmic Rays, & γ-ray production

If the magnetic field has a dipole configuration, then the residence time for charged cosmic ray particles is short, compared to the several million-year time scale in the Galactic disk.

So, a higher cosmic ray production rate can be offset by the much shorter lifetimes of the relativistic particles.

(also the shorter radiation lifetimes)

This can account for the shortfall of cosmic rays from the Galactic center, compared to elsewhere in the Galaxy.

Hunter et al. 1997, ApJ, 481, 205 : EGRET observations of diffuse gamma-ray emission

Pressure of the 3 ISM phases in the Galactic center

1. Molecular gas: ("turbulent" pressure >> thermal pressure)
   $n \sim 10^{3.5-4}$ cm^{-3}, $\sigma \sim 15$ km s^{-1} --> $P_m = 3 \times 10^{-8}$ dynes cm^{-2}
2. Molecular intercloud medium:
   $n \sim 50$ cm^{-3}, $\sigma \sim 30$ km s^{-1} --> $P_{icm} = 7 \times 10^{-10}$ dynes cm^{-2}
3. Hot ISM: $n \sim 0.04$ cm^{-3}, $T \sim 10^8$ K --> $P_x = 6 \times 10^{-10}$ dynes cm^{-2}

Compare to magnetic pressure: $P_B = 4 \times 10^{-8}$ dynes cm^{-2} $B(\mathrm{mG})^2$

Compare to ISM pressure in the disk: $10^{-11 \text{ or } 12}$ dynes cm^{-2}

Star Formation:

Unusual factors affecting star formation near a galactic nucleus, relative to a galactic disk:

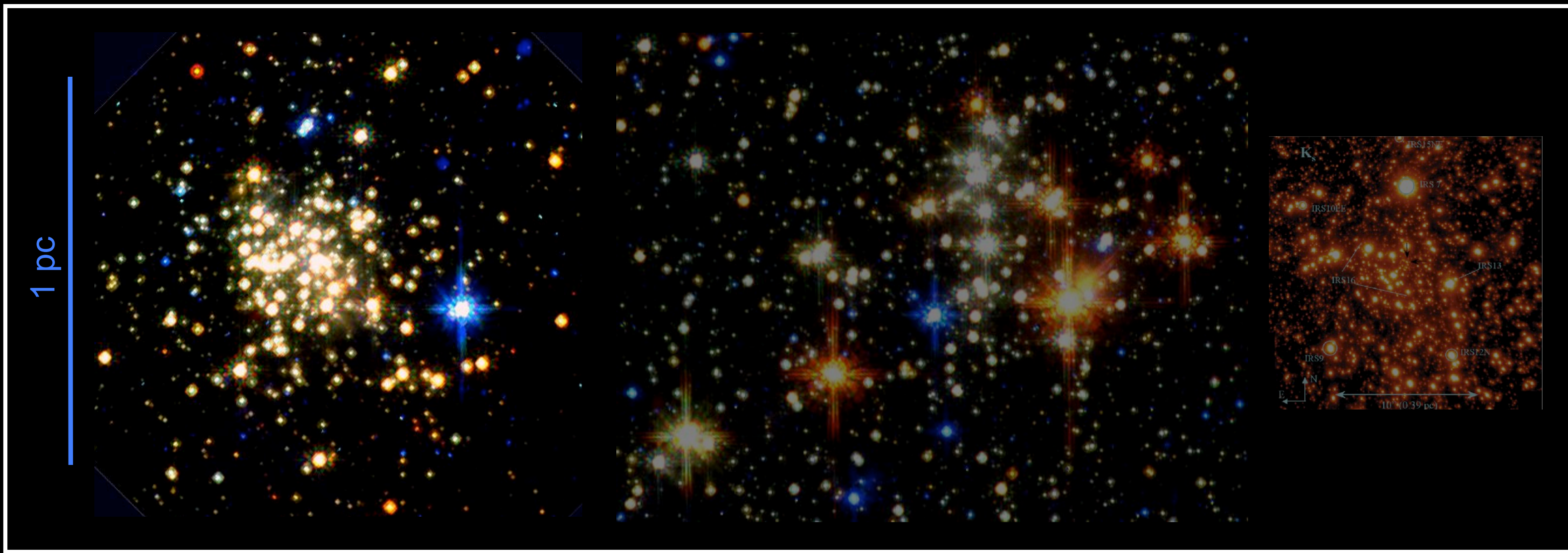
- Molecular cloud surface density
- Cloud temperature, typically 50 - 70 K
- Velocity dispersion within clouds, $\sigma \sim 15$ km s^{-1}
- Magnetic fields -- milligauss?
- Tidal forces, leading to both shear and compression
- Large interstellar pressure
- Metallicity

==>
initial mass function favoring massive stars, relative to disk

- Magnetic Jeans mass α B^3/ρ^2
- M_{Jeans} α $\Delta v^3/\rho^{1/2}$
- Since $\rho\Delta v^2 \sim B^2/8\pi$, these are comparable, and large, 10^{4-5} $M_{\odot}$

Compact, Young, Galactic Center Clusters

Each of these has about one Jeans mass



Arches Cluster, Quintuplet Cluster, Central Cluster
HST· NICMOS, VLT· NOAS· CONICA

Figer et al. 1999; Genzel et al. 2003

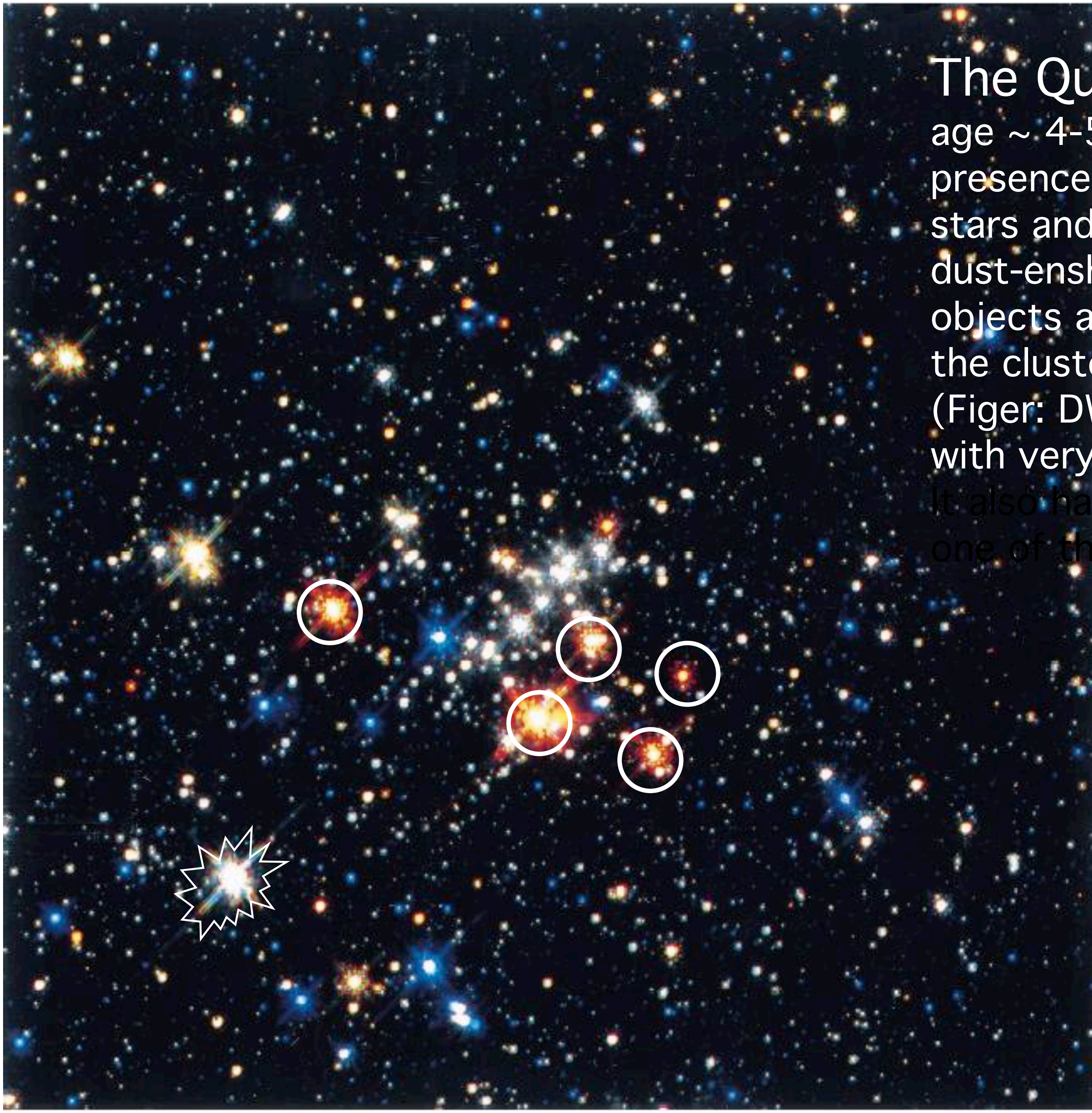
==> Tendency to form spectacular clusters

3 now known. Others would have been seen if they are there or would have left observable remnants if they had disintegrated in the past 10^7 yr.

Arches Cluster:

- ~150 O stars
- initial mass: $2 \times 10^4\ M_\odot$
- luminosity ~= $10^{7.8}\ L_\odot$
- ionizing photon output: 4×10^{51} photons s^{-1}
- age ~ $2.5 \pm 0.5 \times 10^6$ yrs
- 5% of all known WR stars in the Galaxy

Quintuplet Cluster: older (5×10^6 yr), more mature stars.
in later stages of tidal disruption. ~ same initial mass.

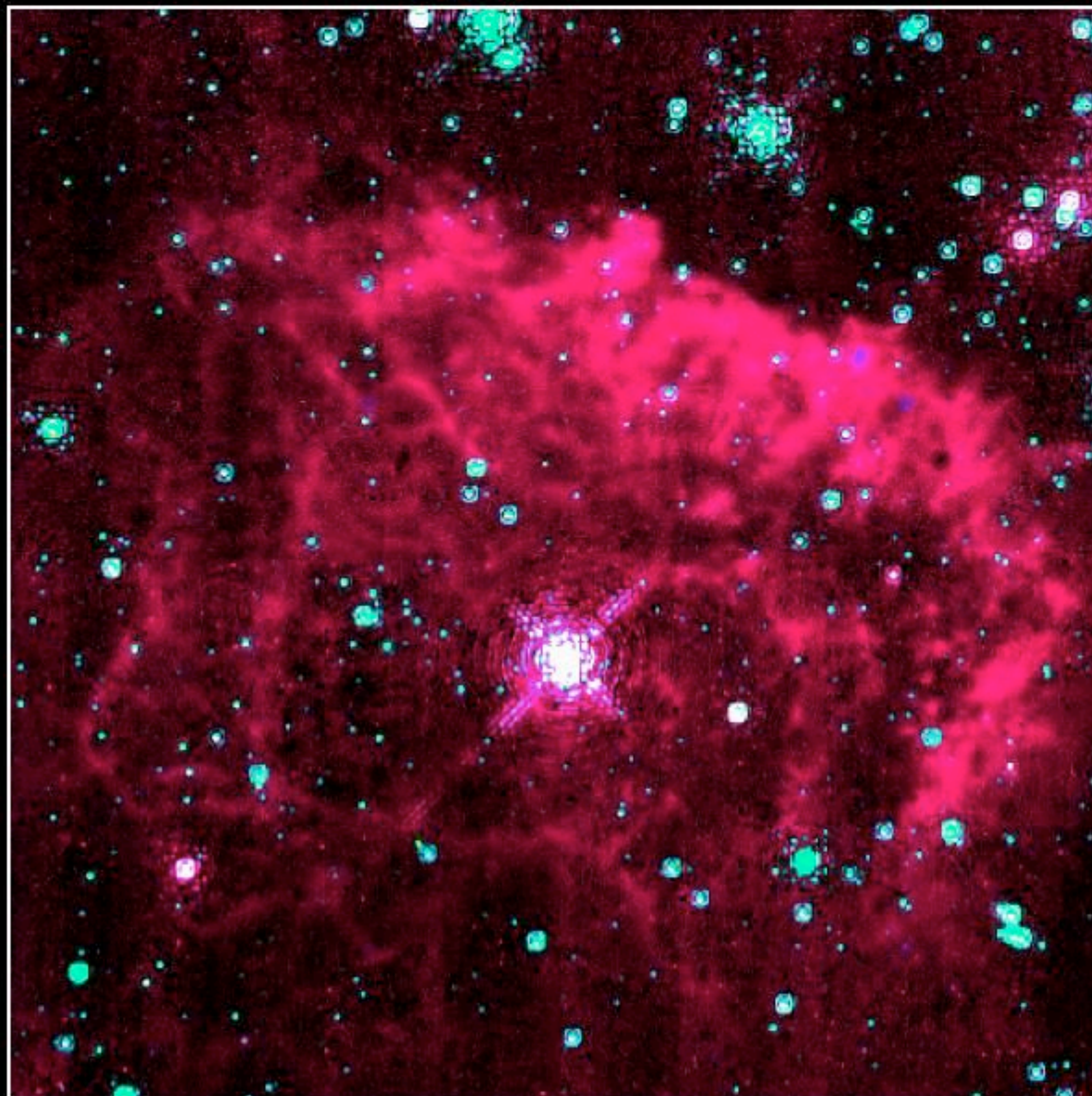


The Quintuplet Cluster

age ~ 4-5 Myr, judging by the presence of WR, LBV, M1a stars and the 5 dust-enshrouded mystery objects after which the cluster is named (Figer: DWCL -- WC9 stars with very dusty winds).

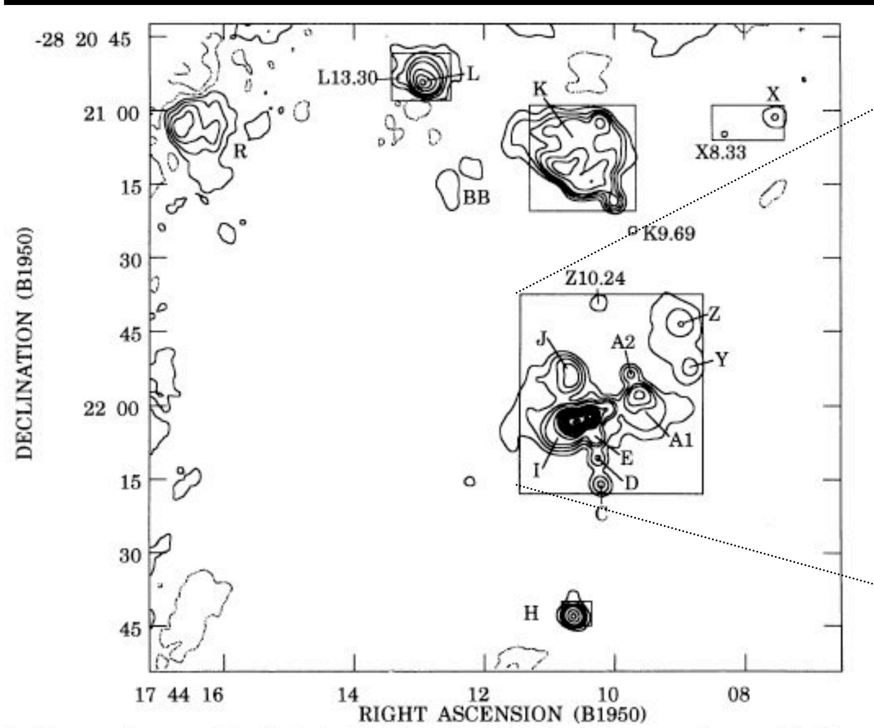
It also has

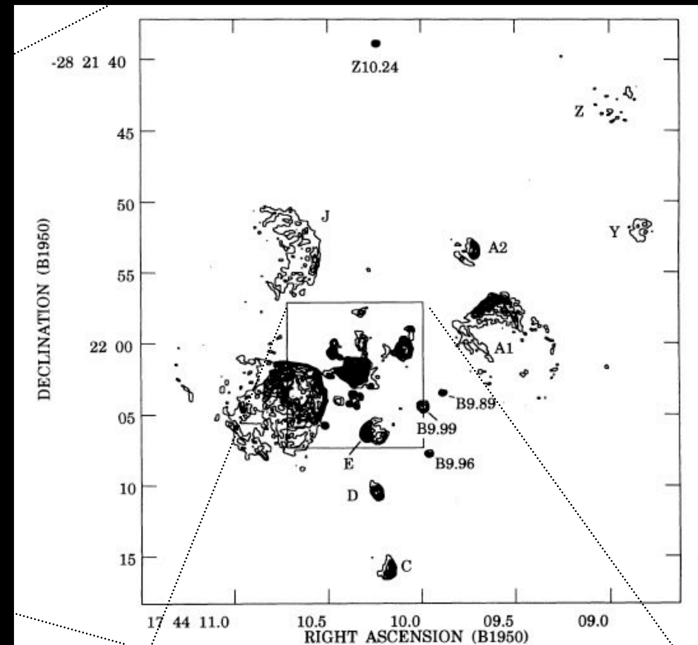
one of th

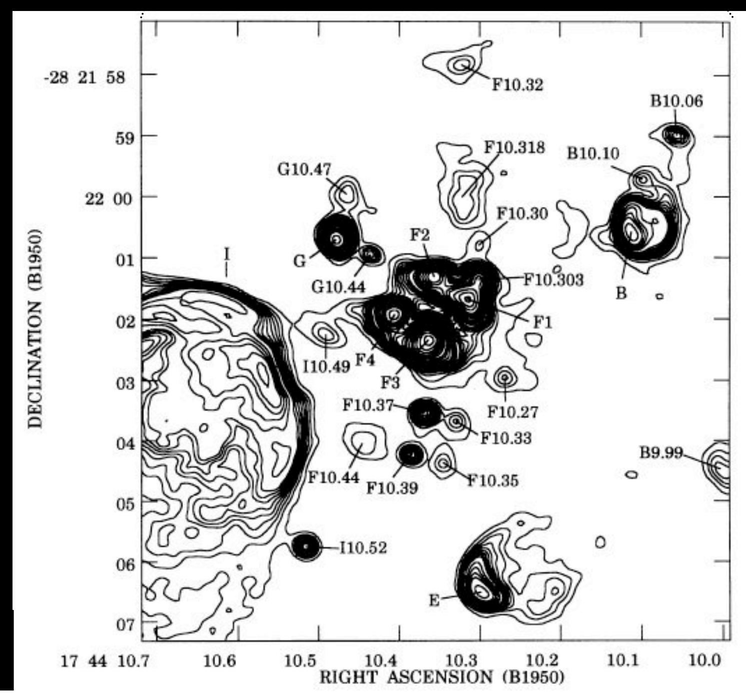


Pistol Nebula and Massive Star HST • NICMOS
PRC97-33 • ST ScI OPO • D. Figer (UCLA) and NASA

Figer et al. 1999, ApJ, 525, 759

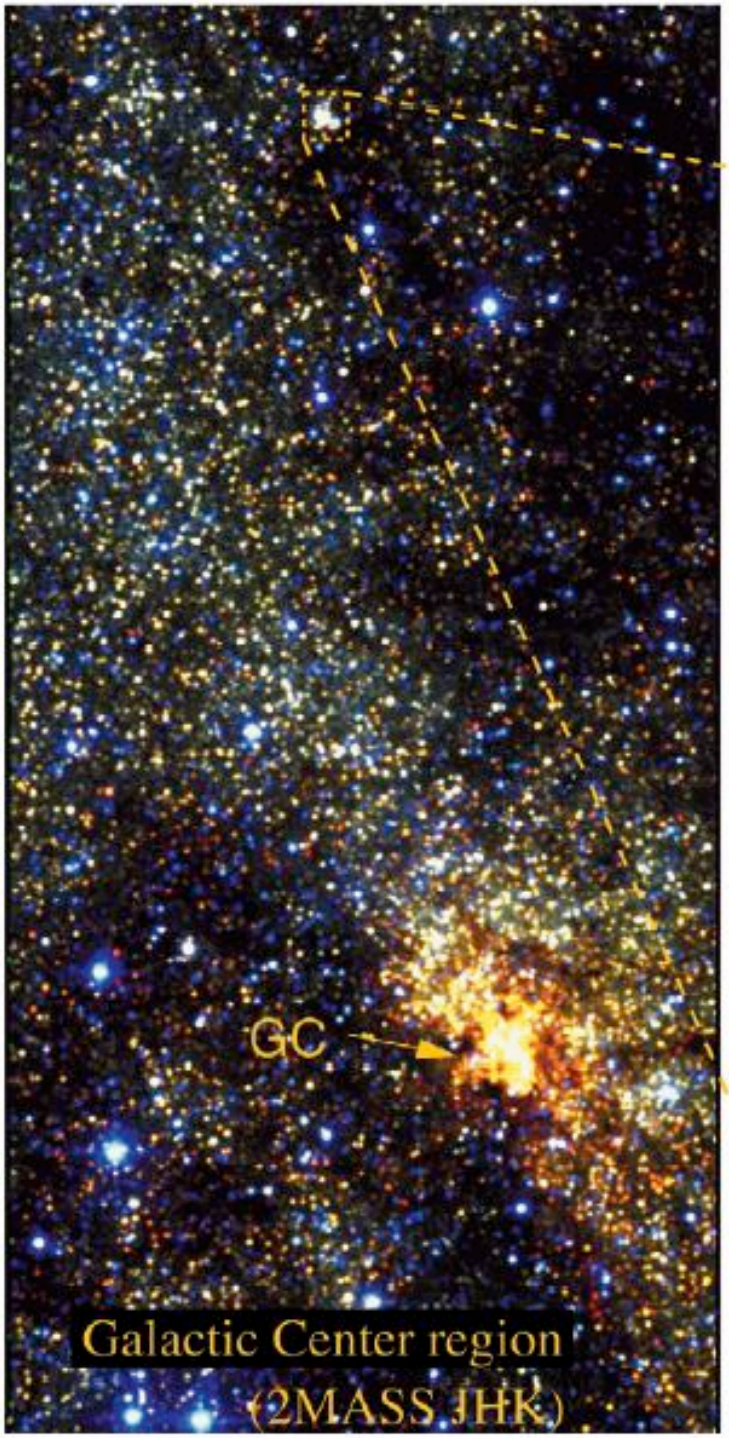






Sgr B2 (Gaume et al. 1995):
over 50 different HII regions in the complex.
-- An Arches cluster in the making?
(perhaps a “messier” version)

From Stolte et al. 2003



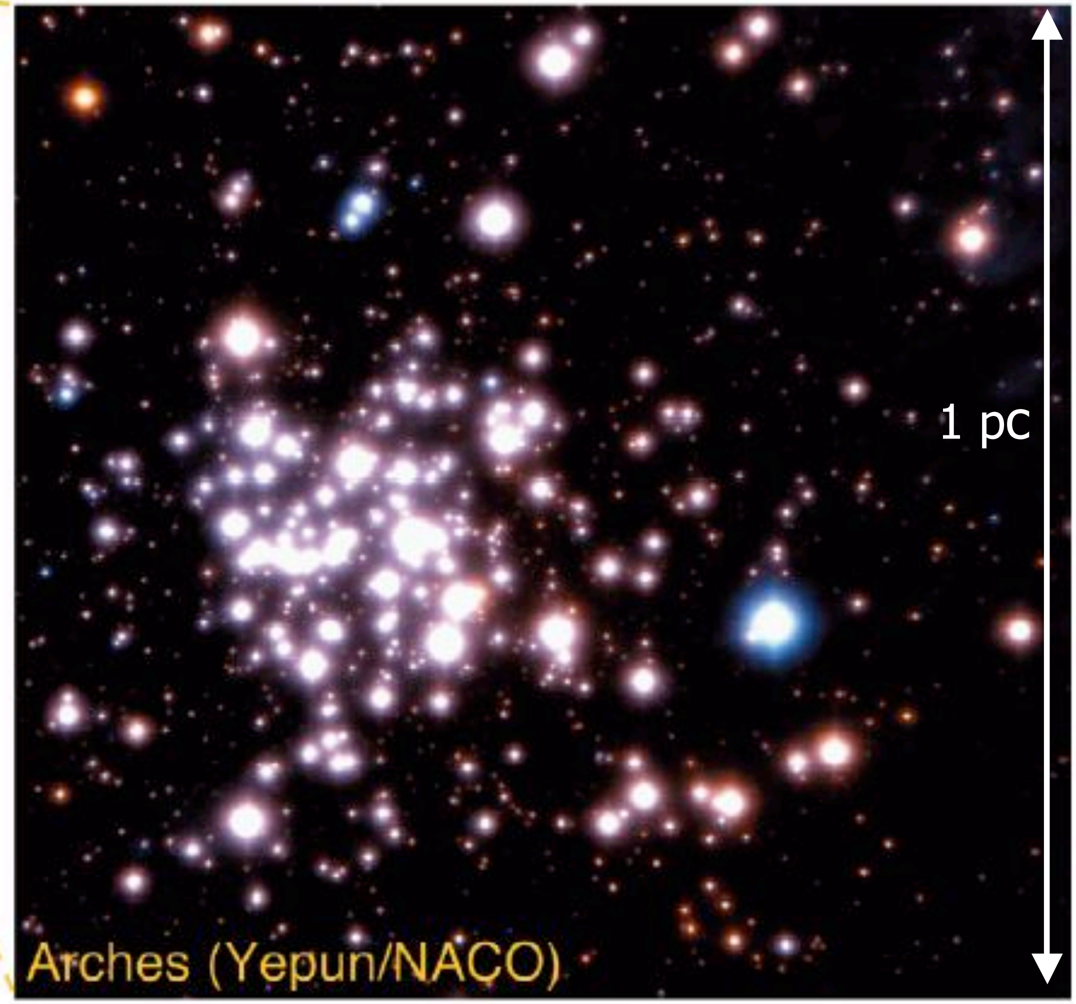
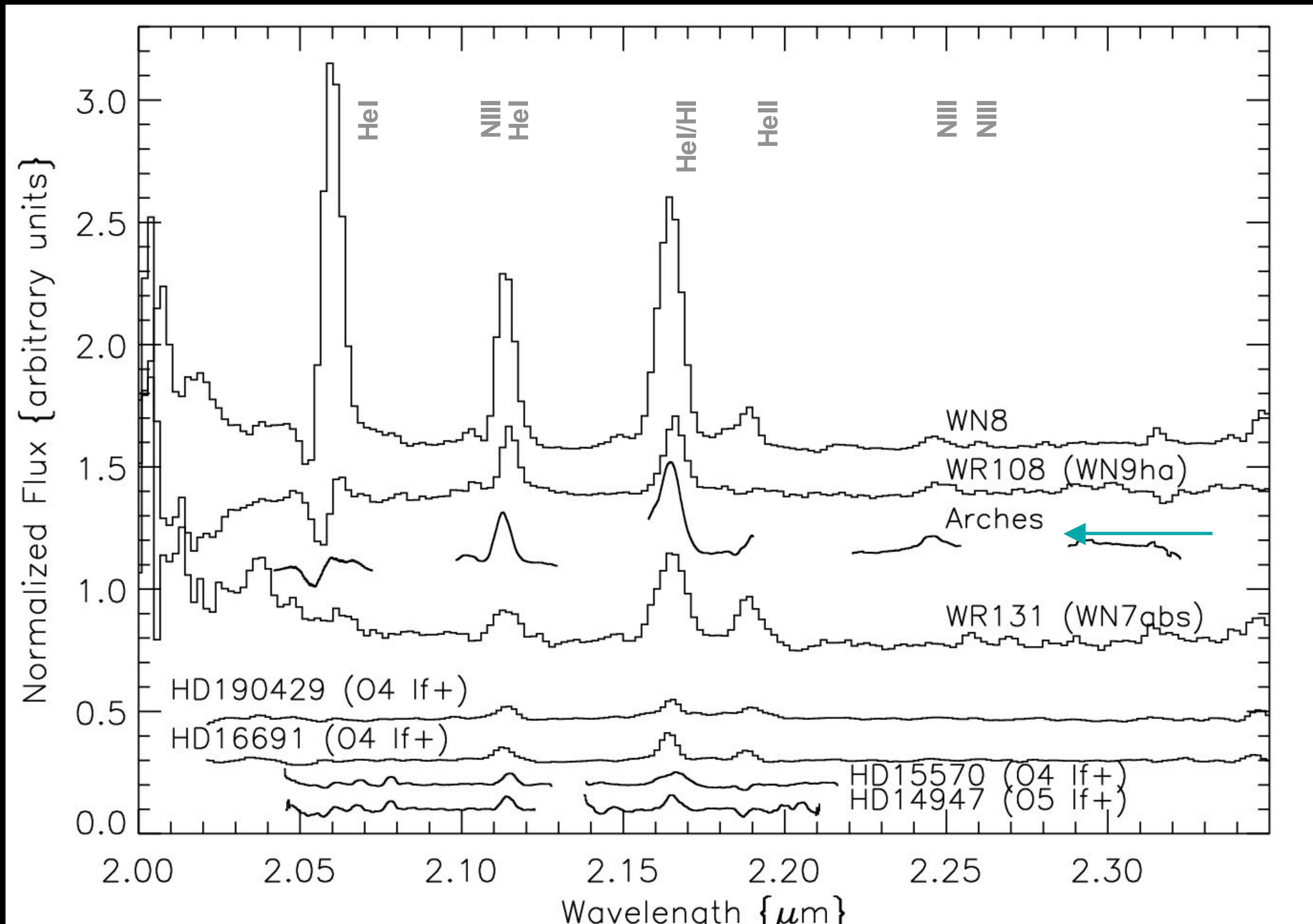


Figure 1: A JHK composite 2MASS image of the Galactic Plane, including the Arches Cluster and the Galactic Centre, is shown in the left panel. The Arches cluster is the little blob of stars pointed out in the North of the image. The CONICA field of view (FOV) is indicated. The NAOS-CONICA H and K_s two-colour composite taken during Commissioning 3 is shown in the right panel. The FOV of this mosaic is 25″ × 27″, approximately the FOV of the CONICA S27 camera. The dense population in the Arches cluster centre has been resolved with NACO for the first time.

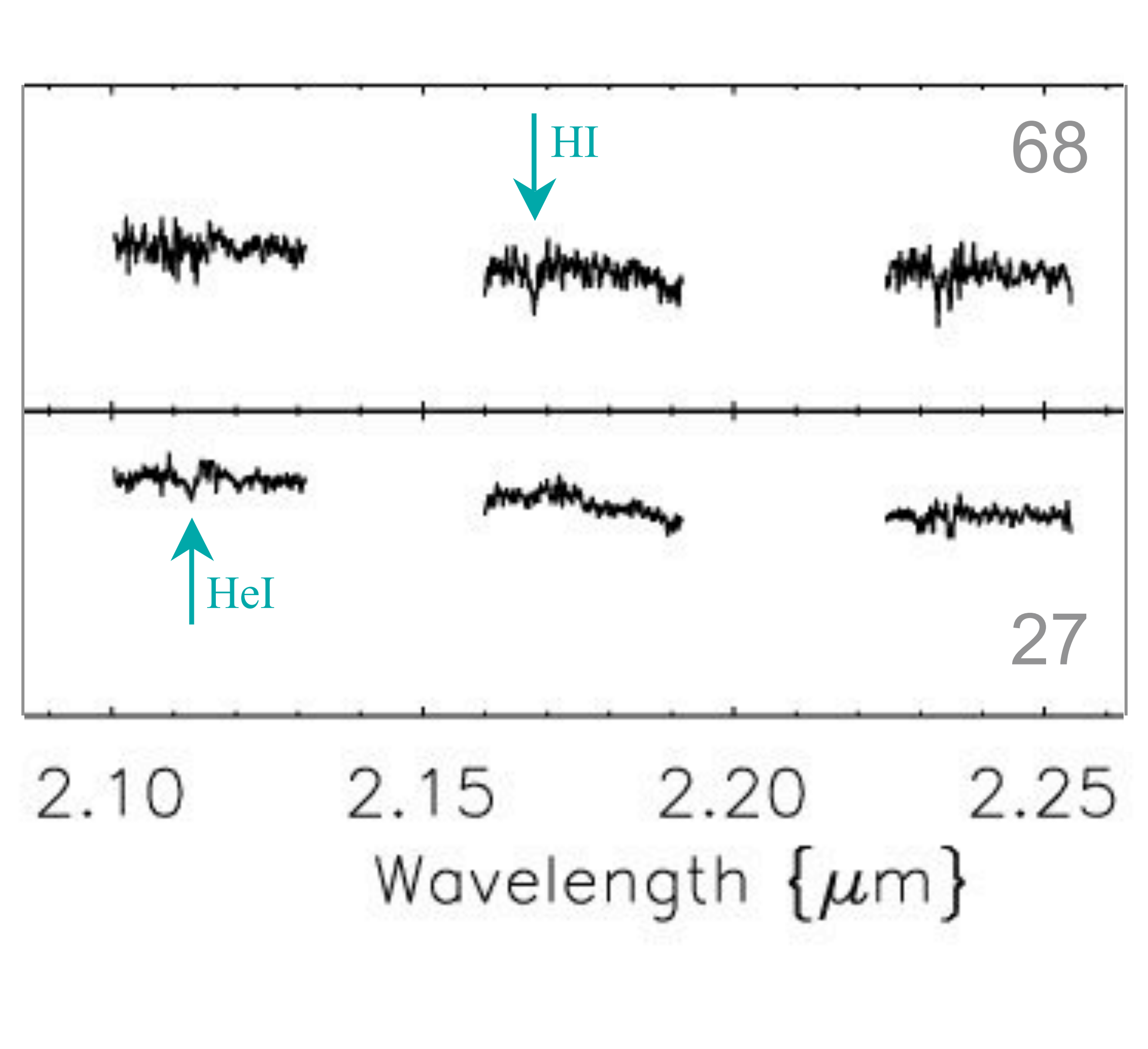
Arches: WN9 stars

Figer et al. 2002, ApJ, 581, 258

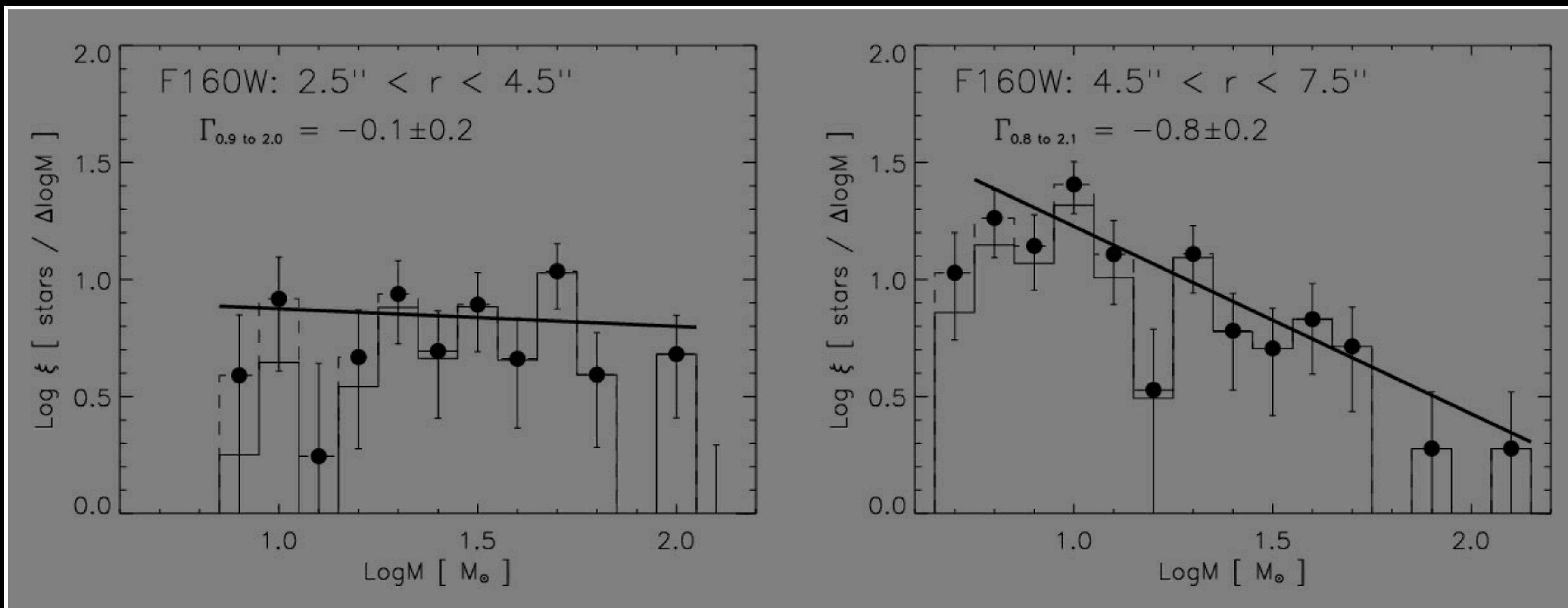


Arches stars: O stars

Figer et al. 2002, ApJ, 581, 258

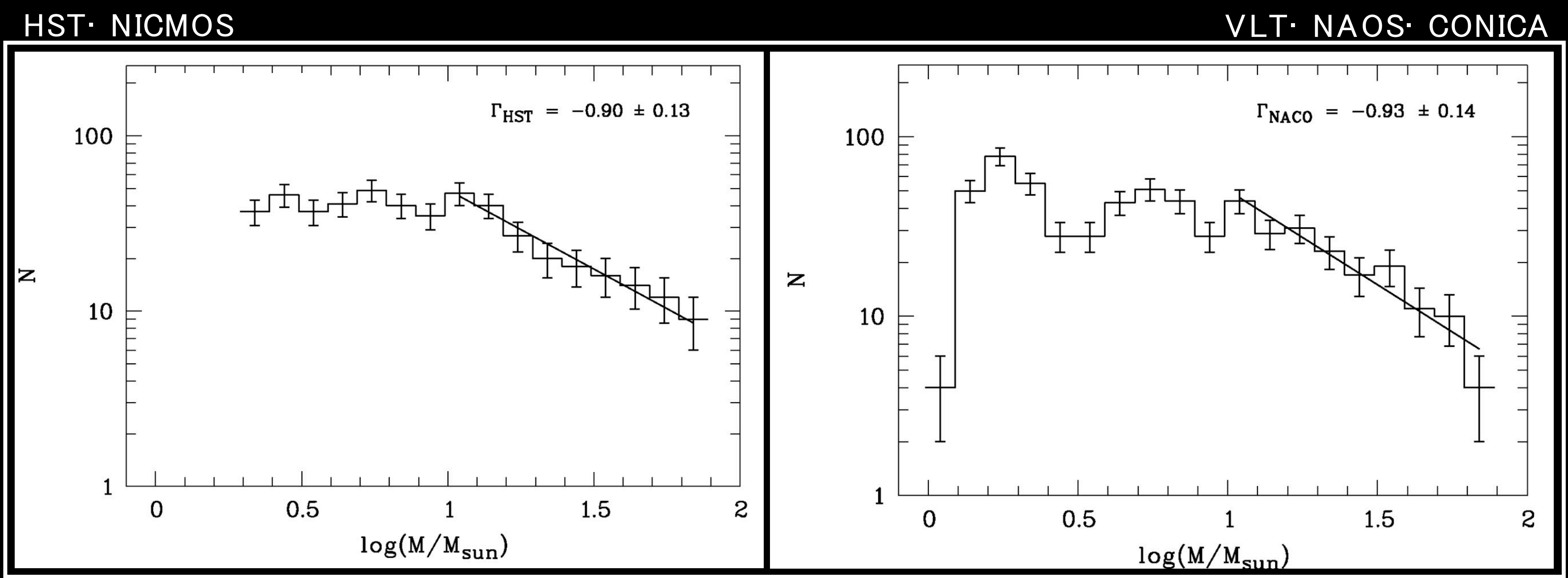


Arches Cluster Mass Segregation



Figer et al. 1999, ApJ, 525, 750

Arches Cluster Mass Function

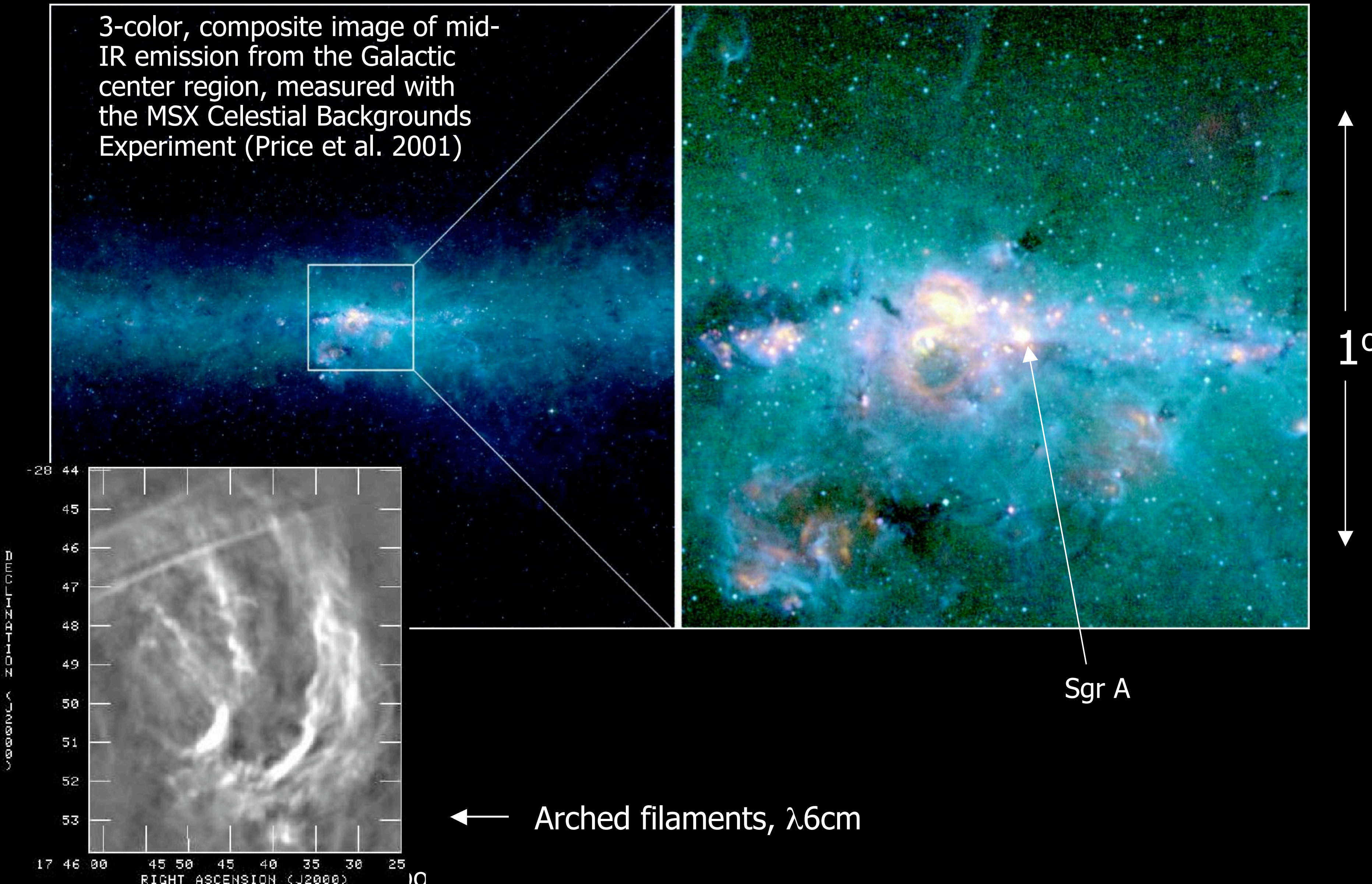


Flat Mass Function in the Arches Cluster

Stolte et al. 2003

Recent result on upper mass cutoff of 150 $M_\odot$ (Figer 2005)

These clusters dominate the energetics of the Galactic Center ISM



Cluster conclusions:

- The massive young clusters account for a substantial fraction of all the star formation taking place in the central few hundred parsecs of the Galaxy.
- Related to super-star clusters? They probably indicate a quite different mode of star formation unique to high-pressure environments.
- Note that the large Jeans masses derived for Galactic center conditions are comparable to the masses of the entire young clusters.

The study of young stars outside of clusters is less well advanced -- clearly, many haven’t been found.
E.g., Muno et al. 2005: X-ray selection of young stars..

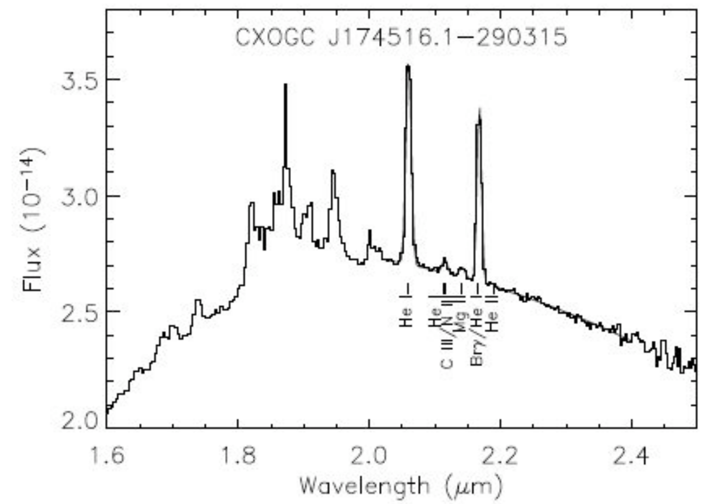
TABLE 1
BASIC PROPERTIES OF YOUNG STARS

Name	ra (J2000)	dec (J2000)	J	H	K	$S_{8.3\ \mathrm{GHz}}$ mJy	Net X-ray Counts	Bkgd. X-ray Counts
new B[e]	266.31744	−29.05434	11.5	9.2	7.9		706±31	170± 4
H2	266.36923	−28.93472	14.3	11.3	9.2		201±18	86± 2
H8	266.40762	−28.95448	15.6	12.3	10.3		<17	52± 1
H5	266.41382	−28.88923	14.7	11.7	10.2		<27	257± 7
SgrA-A	266.46091	−28.98879	15.4	12.4	10.9		52±12	80± 2
SgrA-D	266.4648	−29.00643	17.6	15.2	11.2		<19	53± 1

NOTE. — Positions are accurate to 0.″3.

TABLE 2
X-RAY SPECTRA OF YOUNG STARS NEAR THE GALACTIC CENTER

Infrared ID	N_H (10^{22} cm^{-2})	kT (keV)	Norm	χ^2/ν	F_X (erg cm^{-2} s^{-1})	L_X (erg s^{-1})
H2A	$7.7^{+1.5}_{-1.4}$	$1.2^{+0.2}_{-0.2}$	$1.0^{+1.2}_{-0.5} \times 10^{-4}$	11/11	5.6×10^{-15}	1.4×10^{33}
SgrA-A	6.0^{a}	> 2	$4^{+3}_{-2} \times 10^{-6}$	5/4	1.7×10^{-15}	5×10^{31}
new B[e]	$4.7^{+0.3}_{-0.3}$	$1.3^{+0.1}_{-0.1}$	$1.5^{+0.3}_{-0.4} \times 10^{-4}$	50/37	1.7×10^{-14}	1.9×10^{33}



SgrA East

Maeda et al. 2002
Park et al. 2005
Sakano et al. 2004 (XMM)

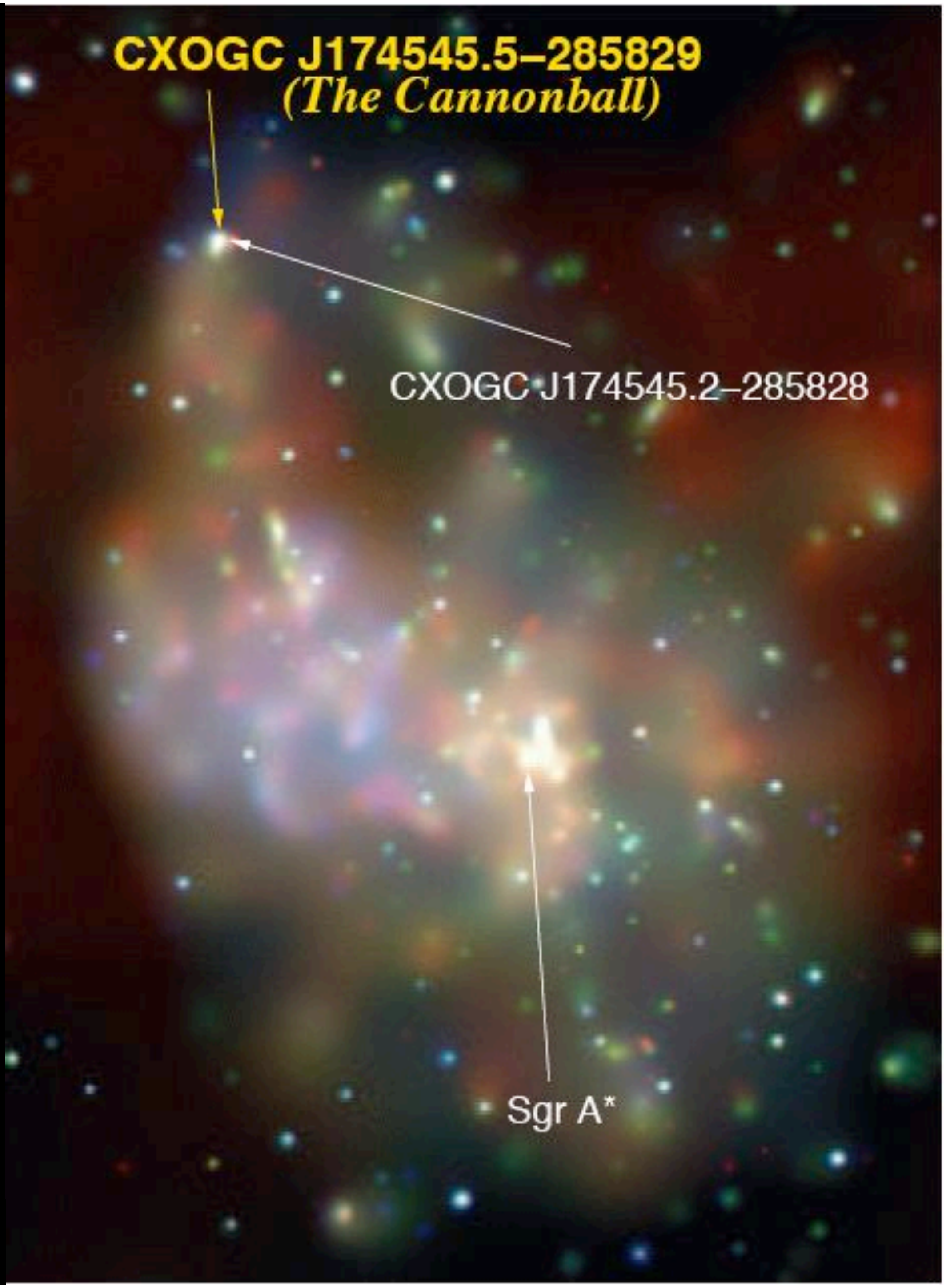
2-temperature plasma (1 & 5 keV), with central Fe enerichment.

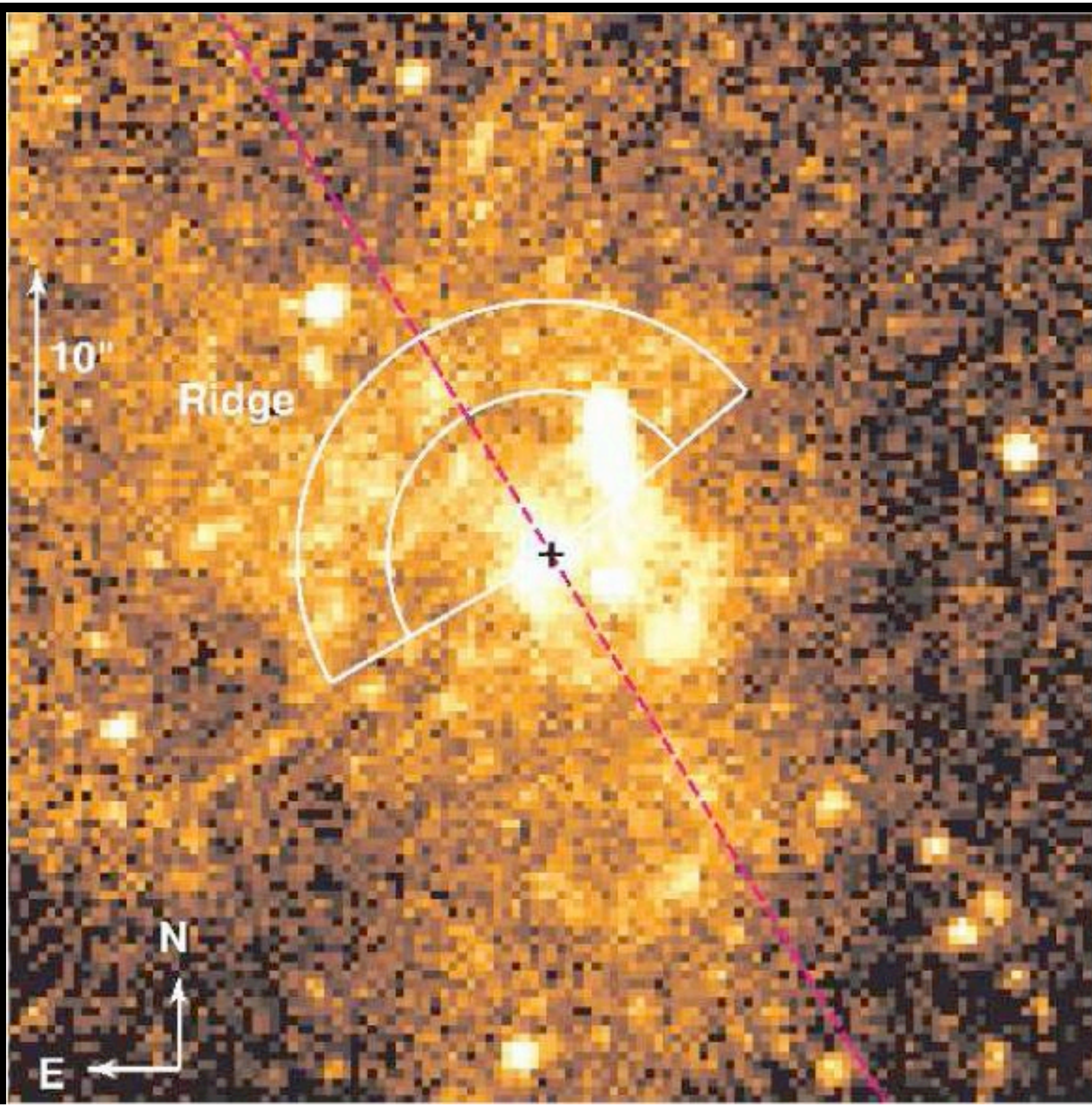
Fe abundance (<0.27 $M_{\odot}$) consistent with a type II supernova.

Age 1700 (Fryer et al. 2005)
- 10000 years.

Interaction with SgrA West?
Rockefeller et al. 2005

See later talk by Fred Baganoff





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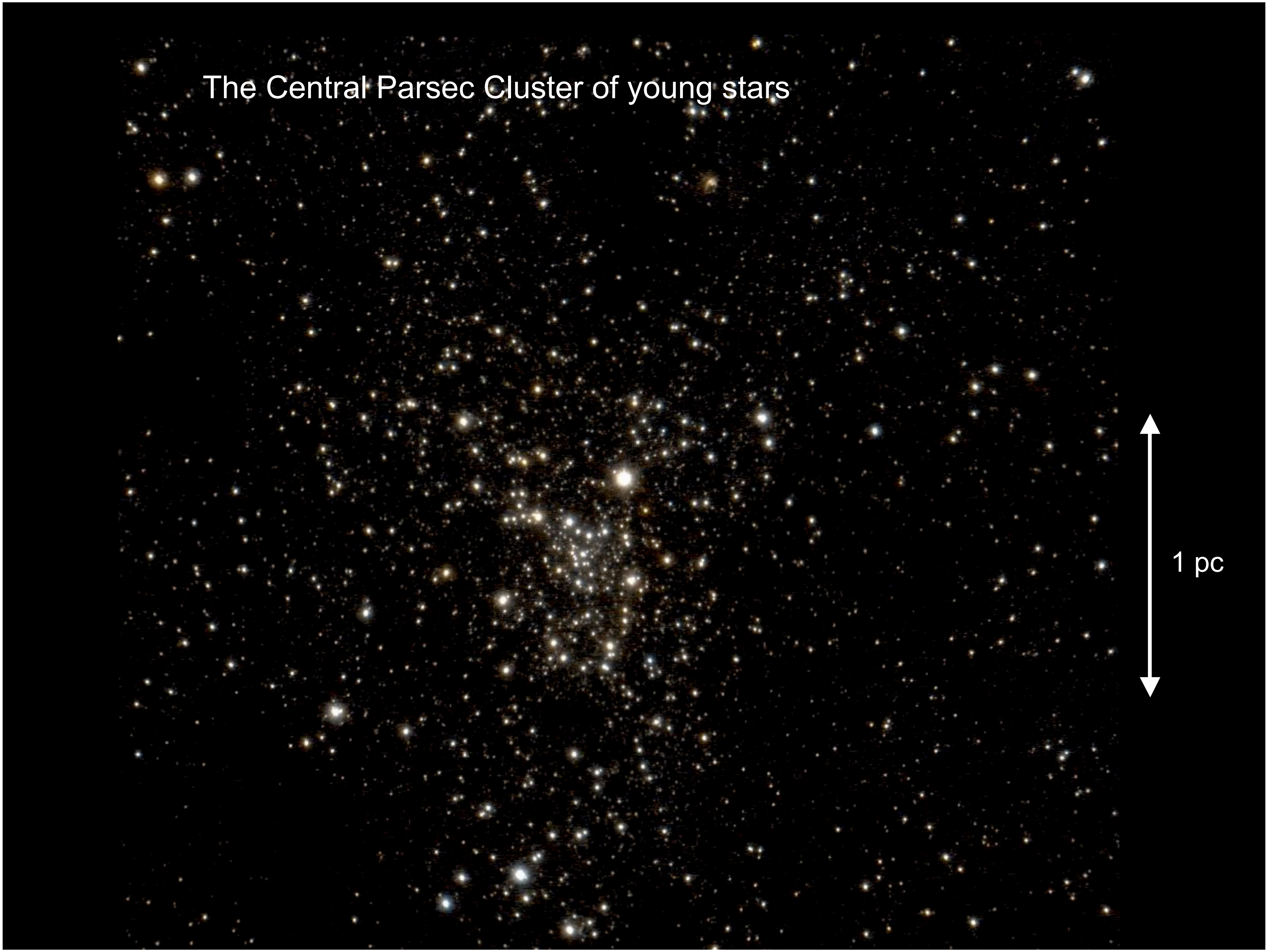
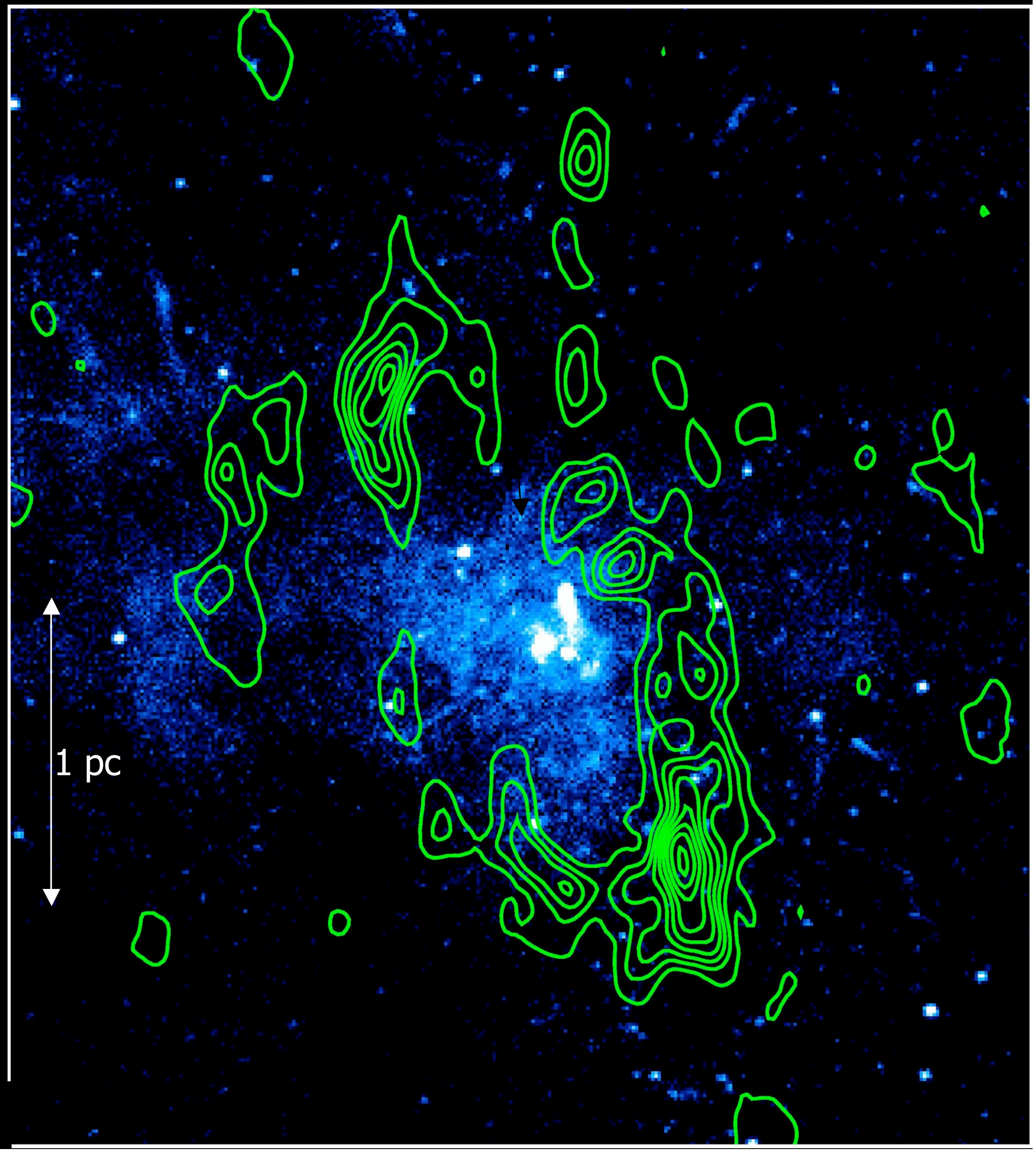

The Central Parsec Cluster of young stars
1 pc

HCN contours from Christopher et al. (2005) on the Chandra deep image of the Galactic center (Baganoff et al.)

→ bound gas clumps may be present in the CND, and it is not unreasonable to imagine star formation occurring there, albeit with outrageous conditions, including “turbulent” velocity dispersions of ~25 km/s and milligauss magnetic fields.

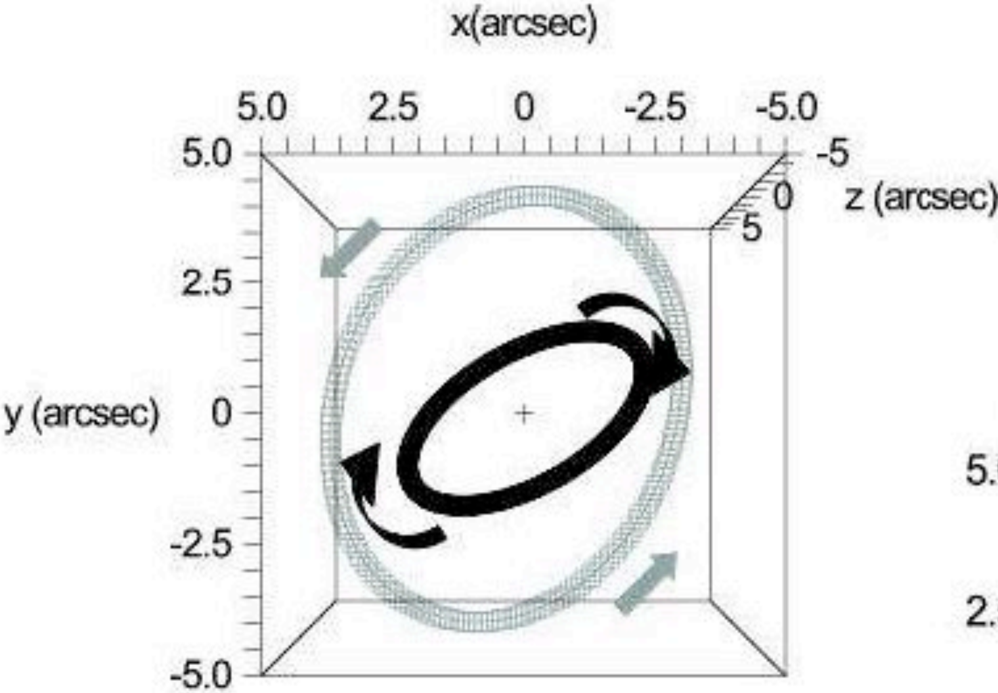
→ The massive stars of the central cluster are *inside* this disk !!!



Kinematics of Early-Type Galactic Center Stars: Counter-rotating disks

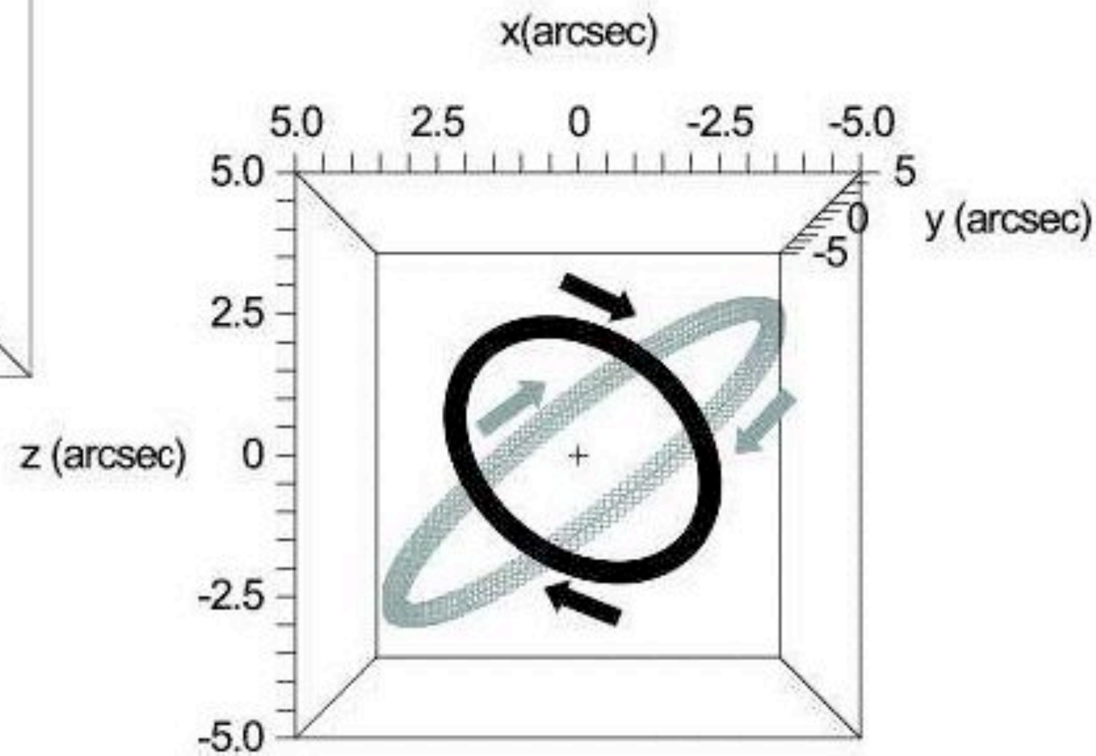
Genzel et al. 2003

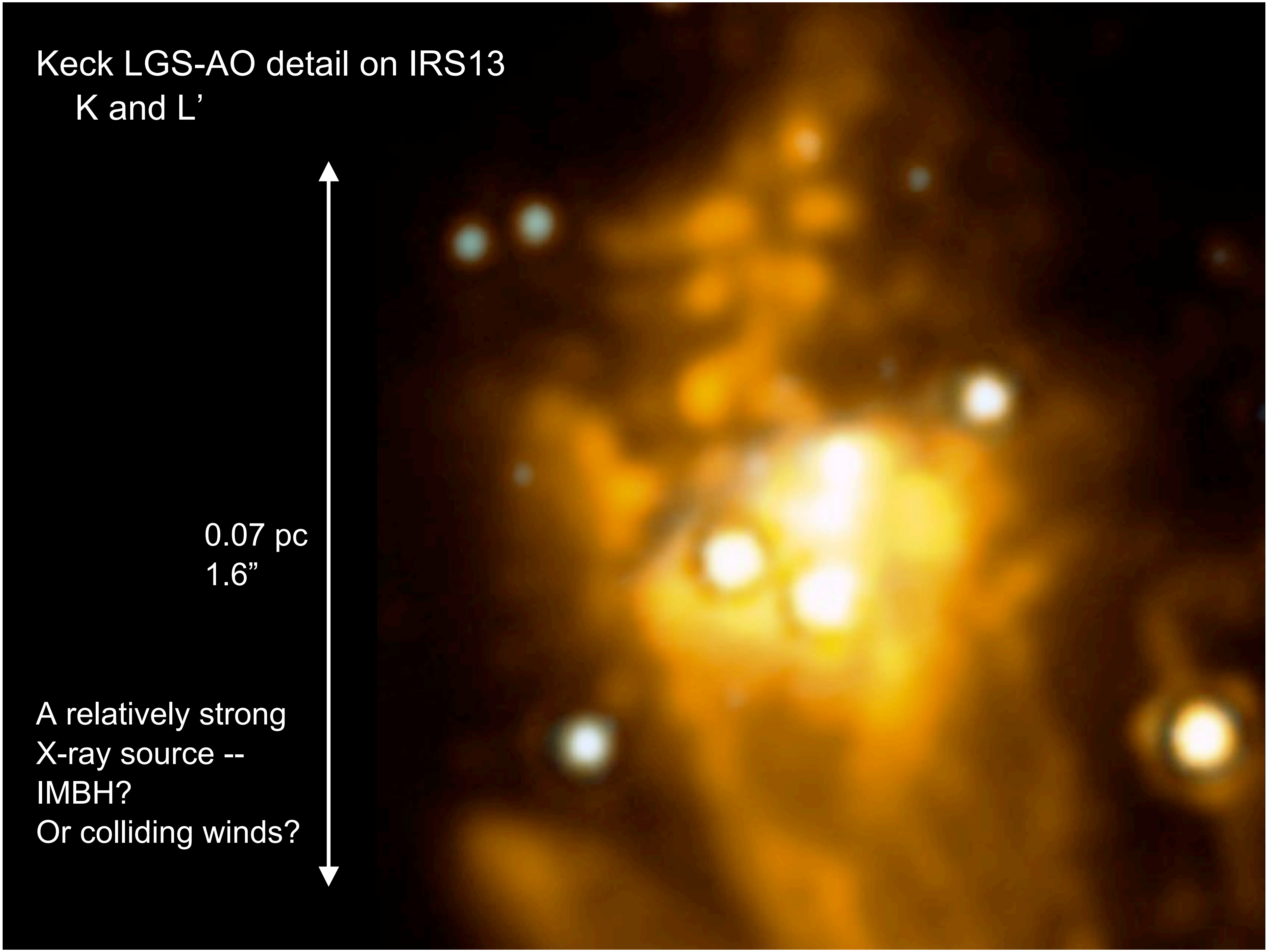
Levine & Beloborodov 2002



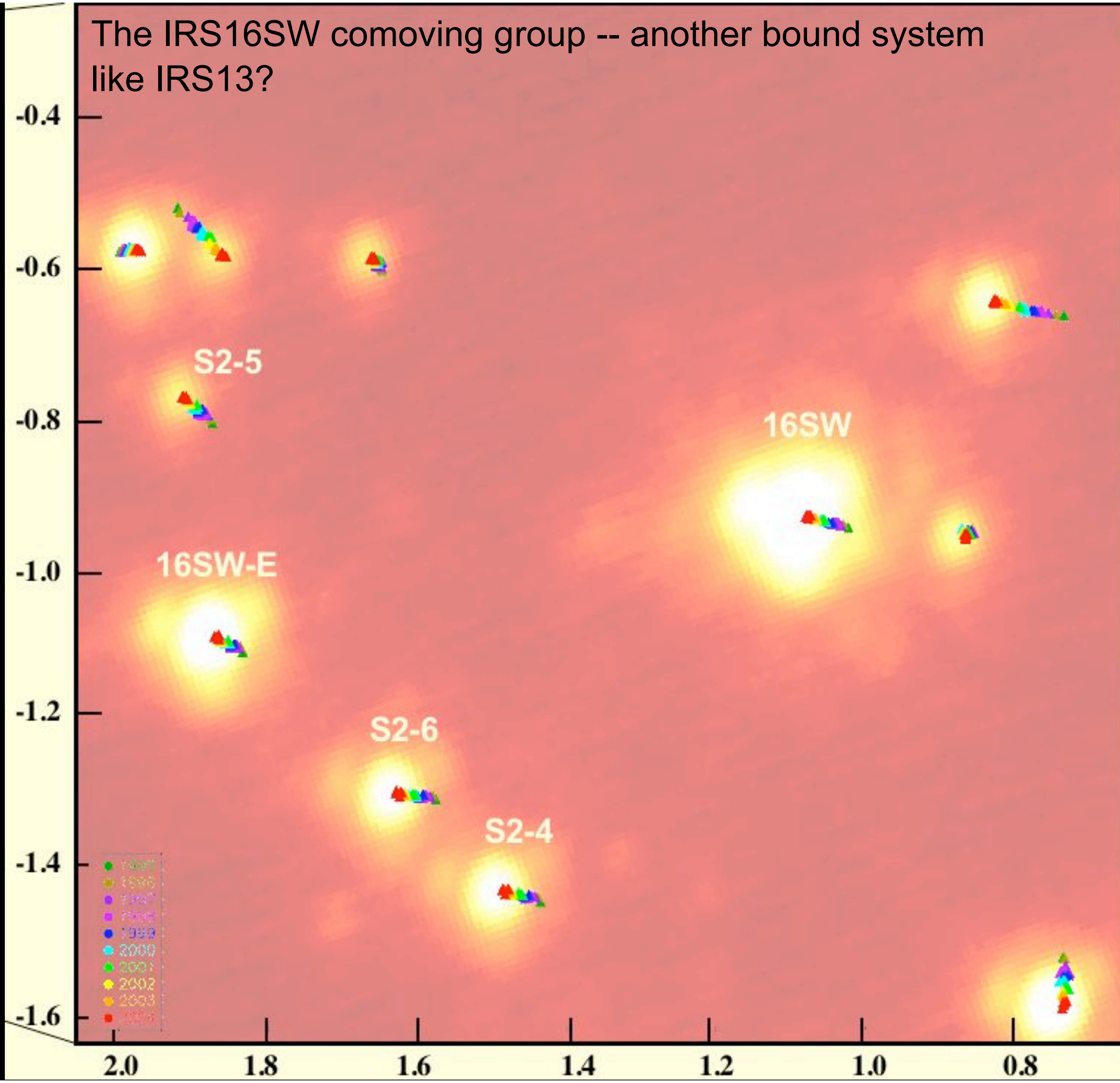
Now: 65 classified stars in central cluster..

54 of them “belong” to one of the disks (Eisenhauer 2005)

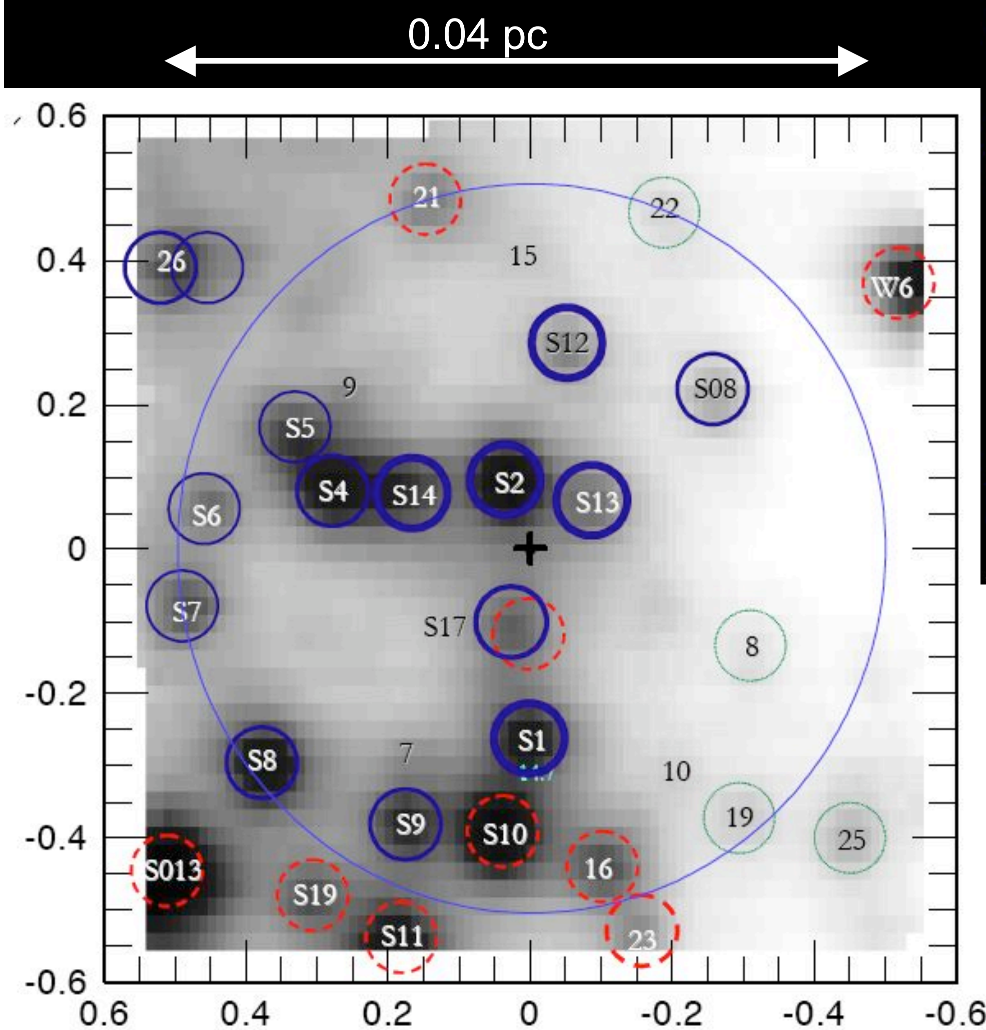



Keck LGS-AO detail on IRS13
K and L’
0.07 pc
1.6”
A relatively strong
X-ray source --
IMBH?
Or colliding winds?

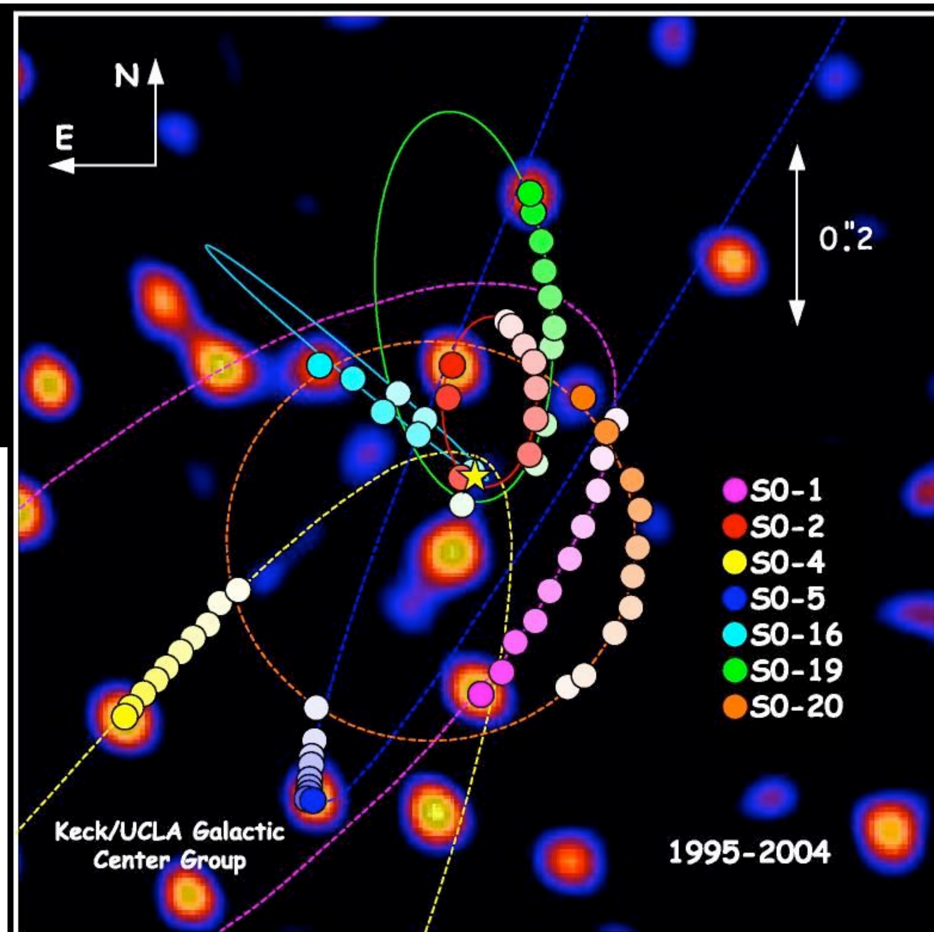
Arcsecond offset from Sgr A*

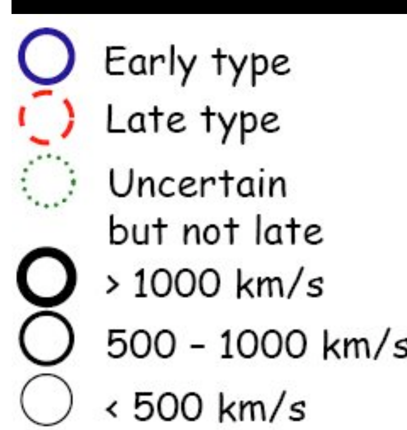


The Central Cusp of Stars
-- mostly B stars
(i.e., no need for exotic objects)



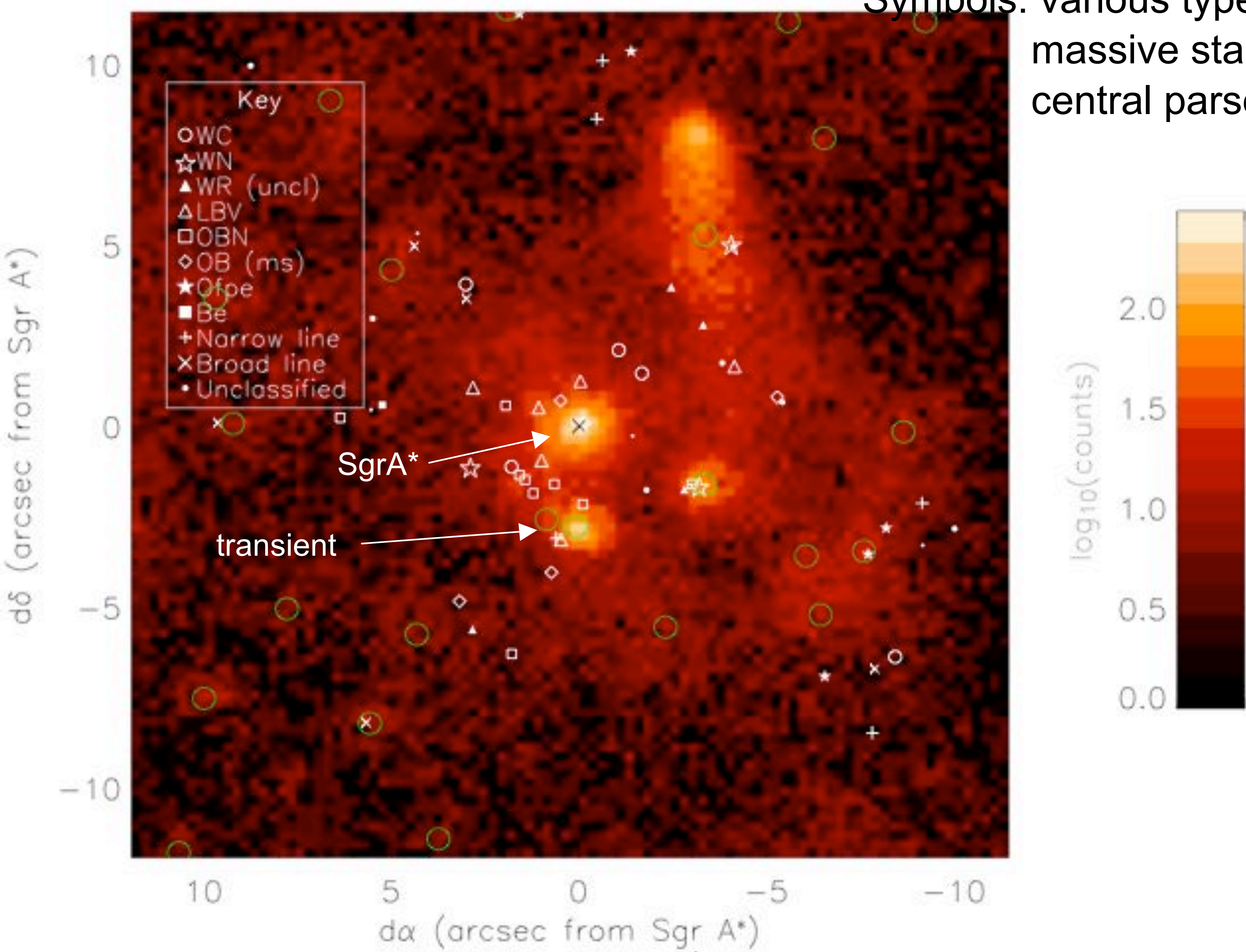
Eisenhauer et al. 2005





Chandra X-ray image of the Central parsec, centered on the X-ray counterpart of Sgr A*

Symbols: various types of massive stars in the central parsec cluster.



X-ray transients support the notion that a cluster of stellar remnants inhabits this region (Morris 1993; Muno et al. 2005)

Is there room for a dark matter cusp at the Galactic center?

- the stellar orbits are Keplerian!
  Limit on any extended dark mass distribution within the orbit of the star S02: 5% M_{BH} (Mouawad et al. 2004; Ghez 2004)
- this can be carried out to larger radii as additional orbits are measured using a combination of proper motions and radial velocities.

Conclusions…

The myriad ways in which particles can be accelerated in the Galactic center environment provides a rich set of possibilities for producing high-energy particles with consequent radiation.

- Fermi acceleration in colliding stellar winds, supernova shocks, and Galactic shocks
- induced electric fields where gas is moving at high speeds relative to the ambient magnetic field
- magnetic field line reconnection
- jet and bipolar outflow from SgrA*
- instabilities in the SgrA* accretion disk
- accretion onto intermediate-mass black holes
- stellar remnants: rotating neutron star magnetospheres & accreting, stellar-mass black holes (microquasars).

GLAST will be an important new step in exploring how these phenomena add to the mix.